School of Science

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# Determining climate change impacts on viticulture in Western Australia

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## DECLARATION

To the best of my knowledge and belief this thesis contains no material previously published by any other person except where due acknowledgment has been made.

This thesis contains no material which has been accepted for the award of any other degree or diploma in any university.

Signature: ………………………………………….

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## ABSTRACT

Global climate model simulations indicate 1.3°C to 1.8°C increase in the Earth's average temperature by middle of this century above the 1980 to 1999 average. The magnitude and rate of change of this projected warming is greater than the average warming during the last century. Global climate models project an even higher degree of warming later in the century also due to increasing grrenhouse gases concentrations in the atmosphere from human activity. Impacts of future climate change on viticulture are likely to be significant as viticulture requires a narrow climate range to produce grapes of suitable quality for premium wine production.

In this thesis, impacts of climate change on winegrape growing conditions across the Western Australian wine regions were spatially and temporally examined by utilising fine resolution downscaled climate projections. Relationships between climate variation and grape maturity or key quality attributes of Cabernet Sauvignon, Shiraz and Chardonnay were modelled from measured fruit and climate data along a natural climate gradient encompassing a 5°C range in winegrape growing season average temperature. Potential future climate change impacts on grape quality were quantitatively evaluated by driving the grape quality models with the downscaled climate projections.

Analyses of climate conditions for winegrape growth were carried out under future climate projections for the Western Australian wine regions. A total of 10 global climate models forced with an A2 emission scenario were downscaled. Of these models, the MEDRES Miroc3.2 and CSIRO Mk3.5 climate models, which indicated the low and high warming ranges (projections of these models will be referred as low and high range warming, hereafter) across the study regions, were selected to take into account the uncertainty of future climate change for impact assessment. Our results indicate increasingly warmer and drier climate conditions for the Western Australian wine regions. The current October to April average temperature (averaged across the regions) is projected to be 0.5°C to 1.5°C

warmer by 2030, respectively. The magnitude of the warming will likely be uneven across the regions. For example, 0.1 to 0.3°C higher average temperature during October to April period has been projected for the northern regions than the southern regions by 2030, depending on the warming ranges. On the other hand, rainfall is projected to decrease across the regions under the future scenario we assessed in this study. By 2030, annual rainfall, averaged across the regions, is projected to decline by 5 to 8%, respectively, under the low and high warming ranges of climate change under the A2 emission scenario. Among seasons, the greatest decline in rainfall is projected to occur during spring. On average, up to 8% and 19% decline in spring rainfall is projected respectively under the low and high warming ranges by 2030.

The magnitude of these changes are projected to increase as time progresses. For example, by 2070, averaged across the study regions, our modelling results show current mean temperature during October to April is projected to be between 1.1°C and 3.9°C warmer, but the annual rainfall is likely to be 15 to 24% lower than the current climate averages (1975 to 2005) under the A2 scenario.

Maturity dates of the studied varieties are projected to advance asymmetrically across the study regions. For example, Cabernet Sauvignon may reach 22 °Brix total soluble solid maturity about 4 and 7 days earlier respectively for the northern and the southern regions by 2030 under the low warming range. Our results also indicate maturity date shifting a further 8 and 18 days earlier by 2070 for the northern and the southern regions respectively under the same warming range. Patterns of this maturity date shifting is likely to be similar under the high warming range. However, the magnitude of advancement is projected to be doubled.

If no adaptive measures are implemented future climate change will likely reduce wine quality due to declining concentrations of berry anthocyanins and acidity under a warmer climate. The reductions of berry quality attributes are likely to be more pronounced in the warmer northern wine regions compared to the cooler southern regions. For example, Cabernet

Sauvignon current median anthocyanins concentration is projected to decline by about 12% and 33% for the warmer northern regions, and about 6 to 18% for the cooler southern wine regions respectively by 2030 and 2070 under the high warming range. In contrast, the maximum decline in Cabernet Sauvignon anthocyanin concentration under the lower warming range is projected to be small, up to 5% for the cooler southern and up to 8% for the warmer northern regions by 2070. Shiraz anthocyanins concentration decrease pattern is similar to that of Cabernet Sauvignon, however, our modelling indicates the magnitude is smaller, with maximum of 18% for Swan District and about 11% for the southern regions by 2070 under the high warming range.

Modelled impacts of climate change on grape titratable acidity are also region and variety specific. Among the varieties studied, Chardonnay exhibits the highest decline in median titratable acidity across the regions (17% for the Margaret River and 42% for the Swan District regions), followed by Shiraz (7% for the Margaret River and 15% for the Peel regions) and Cabernet Sauvignon (no change for Blackwood and 12% for the Swan District regions) by 2070 under high climate warming. On the other hand, the median titratable acidity levels are less impacted by low warming scenario (maximum decline is 4% for Shiraz only by 2070).

Under the future warming scenarios studied in this thesis currently established wine regions and wine styles across the Western Australian wine regions are likely to be affected to the extent that some regions may not be conducive to premium wine production, while for some regions changing the variety may be the only option to adapt to the climate change. For example, by 2070, under high warming range Swan District, Perth Hills, and some parts of the Peel and Geographe regions are projected to be suited more to producing fortified wines or table grapes due to high average growing season temperature (>24°C). In this future climate the present cool climate southern regions are likely to have the same climate conditions that currently prevail in the warmer Swan District. Apparent differences in currently planted varieties between the cooler southern and warmer northern regions clearly indicate the need to adapt to the warming climate in the southern wine regions.

Analysis of other potential factors that influence viticulture such as frequency of hot days, vapour pressure deficit and disease pressure were examined. The results indicated that winegrape fungal disease pressure will likely decrease across the regions due to the declining rainfall, potentially lessening the need for spraying during the growing season. On the other hand, there will likely be increased frequency of hot days and elevated vapour pressure deficit. The impacts of these, combined with the decreasing rainfall during growing season will potentially drive irrigation demand higher requiring altered water management under climate change.

Climatically, most of the Western Australian wine regions are known as premium wine producing areas. The results from this study indicate potential challenges of climate change for the Western Australian wine industry. Under the future climate scenarios examined, some currently warmer regions may become less suitable for premium quality wines due to the increased temperature, which is projected to be out of the optimum temperature range for premium wine production. For most of the other regions, the challenge will likely be a decreased grape quality required to produce premium wine with the current varieties. Suitable adaptation strategies may be required to maintain the current market reputation. Furthermore, the warmer and drier conditions under climate change is likely to necessitate revised water management across the wine growing regions, especially some regions which are already limited by available water for grape production. However, the magnitude of the impacts is projected to be dependent upon the magnitude of future climate change.

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# CHAPTER 1. GENERAL INTRODUCTION

## 1.1 Climate change

There is ample evidence that the Earth's temperature is increasing and the increase is due to elevated concentrations of greenhouse gases in the atmosphere caused by human activity. During the last century the Earth's temperature increased by 0.6 $^{o}$C on average (across different locations) and the 1990s was the warmest decade of the century (Kerr, 2005). Reasons for this warming have been attributed to altered atmospheric radiative forcing due to increased greenhouse gas emissions into the Earth's atmosphere (Le Treut et al., 2007). Development of complex climate models and their ability to accurately simulate past climatic conditions provide an opportunity to project future climate evolution. In turn, these projections may be useful to predict the influence of future climatic conditions on human activities such as agricultural production.

The latest findings of different climate models suggest if grrenhouse gas continue to increase in concentration in the atmosphere further increases in the Earth's surface temperature will result. Global climate models (GCM) project 0.64 $^{o}$C to 0.69 $^{o}$C warmer average surface air temperature between 2011 and 2030 compared to the period from 1980 to 1999 (Meehl et al., 2007). The temperature increase is believed to be more pronounced on land areas than oceans due to the moderating effects evaporation has on warming of oceans rather than land (Christensen et al., 2007). Meanwhile, it is also accepted that a certain degree of future climate warming is already locked in due to the increased concentration of atmospheric greenhouse gases that have been emitted in the past even if all emission are stopped now. This projected climate change is likely to impact a wide variety of existing natural and human devised systems on Earth including ecosystems and agriculture.

## 1.2 Climate change and trends in Australia

The Australian continental average temperature has increased by 0.76 to 0.90 °C during the last century and much of the change occurred in the second half of the century with the average temperature increasing by 0.16 °C per decade since 1950s (CSIRO and BOM, 2007). Strong indications of climate change are readily observed in weather-related incidents over the last decades. With increases in average temperature the number of extremely hot days are increasing (Collins et al., 2000), while the number of cold days and cold nights are decreasing (Nicholls and Collins, 2006). Meantime, it has also been observed that the frequency and intensity of extreme climate events such as droughts (Nicholls, 2004), and extreme daily rainfall are changing faster than mean events over the last 5 decades (Alexander et al., 2007). While it is difficult to attribute any single climate events to increased concentration of greenhouse gases in the atmosphere, projections using climate models indicate an increasing frequency of events such as these in future (CSIRO and BOM, 2007).

## 1.3 Climate change and trends in the southwest of Western Australia

To date temperature changes for Western Australia (WA) is no different from the national trend (Whetton, 2001, CSIRO, 2006, IOCI, 2006). Since 1910 the annual mean temperature has increased by 0.8 $^{o}$C, which is close to the national and global average increase (IOCI, 2005). The increase in daily minimum temperature (0.9 $^{o}$C) is slightly higher than the increase in the daily maximum of 0.7 $^{o}$C. However, in some areas the increases in daily maxima are higher than the minimum temperature changes (IOCI, 2005).

In the early 1900s, the southwest of WA had a consistent and reliable rainfall (IOCI, 2002). However, climate statistics reveal that annual rainfall decreased by 21 to 24 mm per decade during the last century and the change was more drastic during the second half of the century (CSIRO and BOM, 2007). Furthermore, changes were greater during the winter months.

Average rainfall during May to October declined by 10 to 15% during 1976-2001 compared to the preceding 50 years (IOCI, 2002). Decreasing rainfall amounts in the southwest of Australia have resulted in a sharp decrease in surface water streamflow since the 1970s (CSIRO and BOM, 2007).

### 1.4 Future climate projections in the southwest of Western Australia

Different climate models produce different projected outcomes depending on model characteristics and future greenhouse gas emission scenarios. Therefore, projection of a particular climate parameter provides a range of different values (Pittock, 2003). Under different levels of future greenhouse emissions (A2, A1B and B1) conceived by the Special Report on Emission Scenarios (SRES) (IPCC, 2000) average summer temperatures in the southwest of WA have been projected to increase by 0.2 to 2.1$^{o}$C by 2030 relative to 1990 values (Whetton et al., 2005a, CSIRO, 2006, Bates et al., 2008). Further, a 3.2 to 6.5 $^{o}$C warming will likely occur by 2070 in the southwest of WA (Allan and Hunt, 1999, Whetton et al., 2005a, IOCI, 2006). These projections suggest that the southwest region of WA will potentially experience significant changes in its climate system in the next 20 to 70 years.

Rainfall projections produce a range of outcomes depending on the model and also the region of interest in Australia. For the southwest of WA, however, all current CMIP3 models project a decline in annual rainfall ranging from 9 to 22% by 2030 to a 5 to 60% drop by 2070 relative to the 1990 average (CSIRO, 2006, IOCI, 2006, IOCI, 2005, Bates et al., 2008). Reductions in winter and spring rainfalls tend to be more than that of any other season (Hughes, 2003). By contrast, due to disagreement in different models, some areas of eastern Australia are projected to have -10% and some +10% by 2030, and -35% or +35% change in rainfall by 2070 (Whetton, 2001). Potential evaporation is projected to increase up to 10% by 2030 and up to 32% by 2070 over Australia regardless of changes in rainfall (Whetton, 2001). Collectively, these changes have the potential to have large impacts on land use suitability and on ecosystems.

An increased number of hot days, reduced frost occurrences and shortages in water supply in the southwest of WA seem to be visible consequences of recent climate change (IOCI, 2005). Meanwhile, the striking feature of the rainfall projections for southwest WA, unlike the rest of the country, is their consistent decline in both in the short  and long term. The projected decline in rainfall combined with the increasing average surface temperatures will likely amplify the impacts of climate change for the region. Therefore, the potential impacts of these changes on the economy and ecology of the region should not be underestimated.

The above projections are for average climate variables at a specific time period in future. What is often overlooked is that the climate extreme events will continue to occur along with the increase in average climatic values (IPCC, 2001). There are strong correlations between extreme events and mean values both for temperature and precipitation in Australia suggesting that the frequency of future extreme events will increase in line with the changes in mean values (Alexander et al., 2007). For instance, in Perth, the annual average number of days over 35°C is projected to increase by 5 to 10 days by 2030 relative to the current 28 days (CSIRO and BOM, 2007). Meanwhile the average number of days with subzero temperature may decrease by 3 to 9 days compared to the 1990 average in Wandering by 2030 (Whetton, 2001).

Decreased frequency of frost days might have positive impacts on some crops if frost is currently a limiting climate factor. However, this type of positive impact may be surpassed by greater negative impact on yield due to the inevitable parallel increases in extreme hot temperature. For example, up to a 36% drop in corn crop yields were reported for some parts of Europe following the extreme climatic events (up to 6°C warmer than average and precipitation deficit up to 300 mm) during the 2003 summer (Tubiello et al., 2007). However, the extent of impact will depend on the timing of extreme events in relation to the particular development stages of crops for example fruiting etc. Taken together, this suggests that the impacts on agriculture due to extreme weather events, which are often detrimental to agricultural systems, is likely to increase under projected climate change in WA.

### 1.5 Climate and winegrape growth berry quality relationships

The main cultivated species for quality wine making is *Vitis vinifera*, some genotypes of this species can survive temperatures as low as -15 $^{o}$C to -20 $^{o}$C during winter time (Leeuwen and Seguin, 2006). Climate parameters such as temperature, precipitation, humidity, radiation,and wind all affect winegrape phenology, berry development, yield and fruit quality (Gladstones, 1992, Jones and Davis, 2000a, Caprio and Quamme, 2002). Winegrapes can grow and produce fruit in different temperature zones, for example cool climate in Canada to warm climate in Australia, but a particular variety tends to produce appropriate yield and good quality fruit within confined interval of climate variables. Historic evidence, and year to year variations of wine quality in a given place all suggest that premium quality wine making is highly dependent on climate and climate variation, to which grapes are exposed (Storchmann, 2005, Landsteiner, 1999).

During their growing season winegrapes require variety specific heat loads to reach full ripeness. Most of the varieties need at least 1200 Growing degree days with a base of 10 $^{o}$C (Leeuwen and Seguin, 2006). Gladstones (1992) noted that if the ripening month average temperature is lower than 15 $^{o}$C or above 24 $^{o}$C it is unlikely that good quality wines can be produced due to inadequate fruit ripeness or elevated sugar content. Similarly, Jones (2007) demonstrated that quality viticulture regions tend to lie within the 13 $^{o}$C to 22.0$^{o}$C growing season temperature.

Due to their different heat requirements specific winegrape varieties tend to be cultivated in particular regions with climatic conditions suited to that variety (Gladstones, 1992). Hence, climate is one of the important factors for the viticultural industry in a given region to be profitable and competitive. If the climate is to change in the region, then it is likely to influence the focus of the viticultural practices in the region. Based on existing linkages between grown winegrape varieties and climate zones it is reasonable to assume that without adaptation strategies, climate change may result in reduced viability of some regions.

Potential impacts of climate change on the wine industry may limit future sustainability and have become a subject of several climate change studies over the last couple of years. It has been reported that recent changes in winegrape phenology, grape composition (Jones and Davis, 2000a), wine quality (Nemani et al., 2001, Ramos et al., 2008) and grape fruit maturity (Petrie and Sadras, 2008, Webb et al., 2011) were associated with recent warming occurring to date.

Nevertheless, the potential impacts of projected climate change on grape quality parameters are not well understood and have not been quantitatively evaluated in Australia. It is important to address this deficit of understanding as winegrapes are a perennial crop with decades of productive life span. As such, return on investment is a long term proposition and capital investment within this industry requires careful planning.

## 1.6 The wine industry in Australia

The history of the Australian wine industry started about the 1870s (Gregory, 1988), and through technological innovations and effective legislation (Jordan et al., 2007) today it has become one of the world class wine producers and the fourth largest exporter of wine by volume (Wine Australia, 2010). As of 2007, wine export contributes \$2.87 billion to the nation's economy (DFAT, 2008). The Australian wine industry has evolved in various climate zones (Figure 1.1) each producing distinct wine styles and reputations; from cool regions for producing quality table wines to warm to hot regions for fortified and bulk wines (Jackson and Spurling, 1988).

## 1.7 The Western Australian wine industry

History of Western Australia (WA) wine industry started in Swan Valley and full-bodied table wines and fortified wines were the main productions over a hundred years. Cool climate wine production started in 1950s in cooler

Mount Barker and Frankland areas and later it expanded to Margaret River and the southwest of the state. Currently there are nine official wine regions, Geographis Indications (GI), in WA located mainly in the southwest corner of the state encompassing encompass cool and warm climate viticulture and high and low rainfall areas (Figure 1.1).

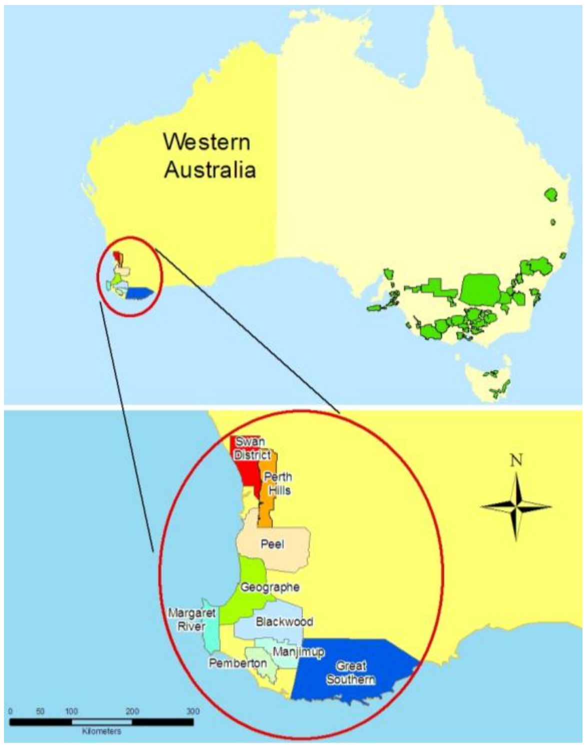


Figure 1.1 Geographic Indications (GIs) of wine growing regions of Australia. Bottom map shows Western Australian GIs.

Production of premium quality grape varieties for the high quality market is the main feature of the WA wine industry. As of 2010, in terms of production volume the WA wine industry contributes 3 to 4.3% to national totals (ABS, 2010, GWRDC, 2009). However, it produces at least 15 to 20% of total value of national production (DAFWA, 2006, GWRDC, 2009) and 1.5% of total national export value despite its small contribution of only 0.8% to the total export volume (ABS, 2010). Climate change impacts on the WA wine industry are not fully known, some regions are likely to be more sensitive to climate change compared with others due to their current differences in temperature regime and water availability for winegrape growth.

## 1.8 Thesis rationale

Taken together, the known climate and winegrape production quality relationships in the past, the observed changes in winegrape production that are attributable to recent changes in climate around the world, and the projected climate changes indicate that the future climate is likely to have impacts on the WA wine industry. In agreement with this, Wine Australia[1] (2007) acknowledged that climate change will be one of the key issues that affect business sustainability in the foreseeable future.

Meantime, potential impacts of climate change on this industry are uncertain and research is required to predict its impacts on the wine industry in Western Australia. Insights on the nature of the impacts of climate change on grape production would help stakeholders in this industry to be prepared to deal with the impacts through adaptation measures. Defining possible adaptation strategies requires understanding of the possible impacts and relative risks to the industry.

## 1.9 General aim of research

To study spatial and temporal changes in climate conditions of WA wine growing regions under projected climate change, and their potential impacts on viticulture

### 1.9.1 Specific objectives of the study

1. To develop empirical grape quality models to explain Cabernet Sauvignon, Shiraz, and Chardonnay quality attribute (anthocyanins, titratable acidity and pH) variations in relation to climate across the study regions

[1] Wine Australia is an Australian Government statutory authority and it provides strategic support to the Australian wine sector

2. To create a fine resolution climate data set for the study regions by downscaling coarse scale climate model output

3. To construct fine resolution spatial surfaces for viticultural climate indices for WA wine regions under different climate change scenarios

4. To develop detailed thematic quality surfaces for Cabernet Sauvignon, Shiraz, and Chardonnay varieties across the WA wine regions

5. To investigate future climate conditions suitable for premium quality wine production across the WA wine regions

# CHAPTER 2. LITERATURE REVIEW

## 2.1 Methodology of approaches to determine impacts of climate change on agricultural crops

A large number of studies have been carried out using different research methods to assess how climate change may affect agricultural production. They address various aspects of climate change impacts on agriculture, from plant growth, changes in production (Singh and Stewart, 1991, Kenny et al., 1995) to implications for farming practices, economy and global food production (Easterling et al., 1992, Parry et al., 2004, Kabubo-Mariara and Karanja, 2007, Ortiz et al., 2008). Two main modelling approaches, plant process-based models and statistical empirical models, are widely used to assess the climate change impacts on agriculture.

### 2.1.1 Plant process-based models

Plant process-based models, such as the Agricultural Production Systems Simulator (APSIM), Erosion Productivity Impact Calculator (EPIC), Crop Environment Resource Synthesis (CERES), and Vine Development Simulator (VineLogic) are based on accumulated knowledge of how a particular plant responds to environmental factors such as weather, soil, nutrition, carbon and management practices. These models are based on plant physiological processes that occur within a smaller time and space (Tubiello and Ewert, 2002). Coupled with projected climate change scenarios, the plant process-based models can be used to assess future climate change impacts on agricultural crops.

Plant process-based models have been used for climate change impact studies for various agricultural crops: wheat (Luo et al., 2005), soybean (Mall et al., 2004), rice (Yao et al., 2007), and winegrapes (Webb et al., 2008a). Having options to manipulate environmental, nutritional and management practices, the plant process-based models can be a useful tool for estimating climate change impacts for different agricultural crops.

However, there are some drawbacks associated with the underlying assumptions of these models.

Firstly, plant process-based models assume that the plant growth processes are totally known, and thus the model parameters can be accurately determined. However, in reality the plant growth mechanisms are extremely complex and can be poorly understood or only tested for a limited range of genotypes (Landau et al., 2000). Secondly, plant process-based models have mostly been developed for a particular place, or region and have a significant empirical base, resulting in less successful projections for other locations (White et al., 1996, Landau et al., 2000).

### 2.1.2 Statistical approaches/ empirical models

This approach relies on empirical relationships between certain climate factor variations and corresponding variations in crop attributes. Empirical models have been widely used for climate change impact studies by using the projected climate variables to drive the statistical models to simulate plant growth under different climate change scenarios. Many studies of climate change impacts have used this approach: farm-land prices (Mendelsohn et al., 1994), wheat yield (Landau et al., 2000), and yields of dominant crops in California (Lobell et al., 2006).

Statistical empirical models are not free of criticism due to their inherent nature of not taking into account the underlying physiological processes of plant growth. For instance, it is common to use statistical models for predicting future climate impacts on a crops yield based on the observed relationships between the yield and the seasonal climate variables. However, from a plant physiological point of view it is inadequate to predict the crop yield using only climate values, as the underlying processes of plant physiology are extremely complex (Landau et al., 2000) and moderated by management decisions. Moreover, correlations among climate variables and non-linear relationships between crop and climate factors make direct statistical prediction complicated (Hansen et al., 2006).

A statistical approach is often used for climate change impact studies on viticulture. For example, Jones and Davis (2000a), Nemani et al. (2001), Storchmann (2005), Jones et al. (2005) and Sadras et al. (2007a) employed this approach to study how vine growth and wine quality responds to observed climate variability in different parts of the vine growing regions. Developing empirical statistical models between climate variables and particular crop attributes, such as yield, is less complex than plant process based models. This makes this approach one of the preferred tools to estimate future climate change impact assessments, however, previously mentioned issues with its reliability need to be addressed.

## 2.2 Climate impacts on viticulture

The connection between climate variables and grape behaviour has been studied and presented in viticulture textbooks and journals (Gladstones, 1992, Jackson and Spurling, 1988, Jackson and Lombard, 1993, Tonietto and Carbonneau, 2004). Gladstones (1992) examined the effects of climate parameters such as temperature, sunshine hours and seasonal rainfall distribution for grape vegetative growth, fruitfulness, and composition of berries. Relationships between climate variables and grape phenology are also well documented elsewhere (Coombe, 1988). The known relationships between climate and winegrapes are used to identify suitable regions for grape production in Australia within a context of past climate.

### 2.2.1 Winegrape phenology responses to recent climate change

Research results show that winegrape phenological events are changing due to climate change. Jones and Davis (2000a) observed phenological shifts, changed berry composition and trends towards increased quality for Merlot and Cabernet Sauvignon varieties in the Bordeaux region along with increases in the number of warm days and decreases in precipitation during maturation. A recent study in Italy also showed earlier bud break (3 days), bloom (4 days), véraison (3 days) and harvest (8 days) in Conegliano region with every 1°C degree during the phenological events (Tomasi et al., 2011). Other studies have also found that to date climate change has led to increased quality and yields in California, but warned that the future climate might not be beneficial due to other negative factors such as disease outbreaks due to high humidity, that could arise as the climate changes further (Nemani et al., 2001).

Winegrape phenology, particularly the timing of events, is associated with climatic factors with certain deviations in a given region. However, research results suggest that changes in climate affect these deviations. For instance, earlier blooming (7 days ) has been observed in the northeast of the United States and it is believed that this shift has been caused by recent changes in climate (Wolfe et al., 2005). Hayhoe et al. (2004) claimed that the average ripening period will start 1 to 2 months earlier by the end of this century and it might lead to reduced grape quality in all regions of California.  These findings taken together with the magnitude of future climate projections suggest that winegrape phenology might be significantly altered in the southwest of Western Australia in coming decades.

### 2.2.2 Winegrape yield, fruit and wine quality

Climate change is likely to impact not only winegrape phenology, but also other characteristics of production such as yield and fruit quality. Chloupek et al. (2004) observed positive relationships between elevated temperature or more sunshine hours and crop yields. Lobell et al. (2006) evaluated climate change impacts on yields of several perennial crops including wine and table grapes in California. This research (Lobell et al., 2006) reveals that most of the perennial crops have nonlinear correlations with climate variables and that climate warming is likely to reduce major perennial crop yields in California.

Berry colour and aroma are important attributes responsible for winegrape fruit quality. The concentration of the compounds characteristics is influenced by many factors such as grape variety, rootstock, soil type, and climate forces (Gladstones, 1992, Jacometti et al., 2007). When other factors are held constant, then climate is the dominant factor influencing the development of berry quality components for given varieties in a given region. Therefore, it is likely that the projected changes in climate will impact grape quality.

Wine quality is also affected by climate as grape quality is the most crucial determinant of wine quality. Jones and Davis (2000a) described shortened phenological interval shifts and quality changes in the Bordeaux region in relation to climate change. According to their research, the impact of climate on grape production is likely to be uneven across varieties, and for a given variety the magnitude of the impacts would also be different depending on the phenological stages of the grapes (Jones and Davis, 2000a). The study by Jones et al. (2005) suggests that future climate change will affect wine qualities either positively or negatively across the world's vine growing regions depending on the current climate. A more recent study in Spain reveals that warmer growing seasons have improved wine quality while causing earlier phenological timing and decreased yield, possibly due to a possible combination of water shortage and heat stress (Ramos et al., 2008). The studies cited above used long term climate and grape data to establish an empirical relationship of how the quality varies in response to changes in climate.

A negative correlation between grape quality and either reduced rainfall in the beginning of the growing season or increased rainfall for the last months of the season has been found in France and Italy by Jones and Storchmann (2001) and Grifoni et al. (2006), respectively. The effect of temperature on winegrape production is likely to be dependent on the magnitude of the temperature increase and the region. For example, Storchmann (2005) states that a 1°C warming during the entire growing season in the Rhine region increases the probability of harvesting a top vintage by 20 to 50%, suggesting that wine growers in that region would benefit from climate change if the warming is moderate. Jones et al. (2005) state that climate in many European cool climate regions, including the Rhine Valley, is close to its optimum for producing the best quality wines. Overall, the climate change impact studies on viticulture produce different results depending on research method, study region, data used and the climate component considered.

There is a general consensus that elevated carbon dioxide ($CO_2$) concentration could increase plant production through enhanced photosynthesis (Bazzaz, 1990, Idso and Idso, 1994). Results from elevated $CO_2$ treatment on vineyards also indicate that grape yield could be increased considerably (Bindi et al., 2001, Bindi et al., 1996).

Levels of atmospheric $CO_2$ will likely increase in the future, but the consequences of elevated $CO_2$ on viticultural regions are still unclear (Schultz, 2000). In contrast to these direct and positive effects of elevated $CO_2$ on winegrape yield, future warming, indirect effect of $CO_2$, may not be beneficial for grape yield through elevated humidity, which in turn could increase the favourable conditions for some winegrape diseases, for some viticultural regions, for example in California (Nemani et al., 2001). Given the uncertainties surrounding the future greenhouse gas emissions and warming, it seems difficult to accurately assess the full impact of elevated $CO_2$ on winegrape responses in field conditions.

### 2.2.3 Climate change and winegrape disease

Outbreaks of winegrape diseases, especially fungal diseases, are promoted by certain weather conditions such as warmer temperature or high relative humidity (Gladstones, 1992, Jailloux et al., 1999, Belli et al., 2005). Existing winegrape disease patterns are likely to be impacted by projected future changes in temperature and precipitation. Chakraborty et al. (1998) noted that excessive canopy growth and density, hence increased duration of leaf wetness, triggered by elevated $CO_2$, or any wet or warmer conditions caused by climate change are likely to increase winegrape diseases that could be disastrous to the Australian viticultural industry.

A downy mildew simulation study in Italy predicted an increase in disease pressure due to favourable conditions created by temperature increase (Salinari et al., 2006). Due to more favourable conditions for downy mildew, the timing of outbreaks is projected to advance in viticultural regions both in the northern and Southern Hemisphere (Salinari et al., 2007). What is striking about this is that the conditions for downy mildew, enhanced by temperature increase, will outweigh the reduced disease conditions caused by declining precipitation (Salinari et al., 2006) for some viticultural areas, Italy in this case, suggesting elevated potential disease risk to viticulture posed by future warming.

### 2.2.4 Climate extreme events and winegrape

As mentioned in the previous chapter, climate change will increase the frequencies of climate extremes globally and regionally (Easterling et al., 2000, Whetton, 2001, CSIRO, 2006, Christensen et al., 2007). Grape physiology is not immune from climate extremes. For example, extreme temperatures between 35°C to 40°C or more, could cause significant damage to grape quality and reduce the yield (Jackson and Spurling, 1988). High temperature combined with strong wind and low humidity could cause more damage to vines and fruit than high average temperature alone (Gladstones, 1992).

White et al. (2006) project that extreme temperature during the growing season affects the grapes more than the changes in mean climate; and that the premium wine growing regions of the United States will decline by more than half by the end of this century due to increases in extreme days. This study suggests that increased temperature, and thus heat accumulation is likely to force wine producers to shift to warmer climate varieties to avoid low quality wines.

### 2.2.5 Relevant studies in Australia

Winegrape climate niches have been studied in detail with regard to the Australian current climate systems (Dry and Smart, 1988, Jackson and

Spurling, 1988, Gladstones, 1992, Hall and Jones, 2009). However, to date, not many studies have been carried out to address past and future climate effects for the Australian grape industry.

Sadras et al. (2007a) quantified time trends of vintage scores, wine quality rating, for Australian wine regions and observed an inverse relation between long term daily mean temperature during the month prior to harvest and the rate of change in white wine vintage score variability. Petrie and Sadras (2008) reported advanced maturity and harvest date for Chardonnay, Cabernet Sauvignon, and Shiraz for 18 wine regions between 1993 to 2006. This study (Petrie and Sadras, 2008) also showed increasing sugar concentrations for Cabernet Sauvignon and Shiraz, and negative correlations between rate of harvest date change and rate of changing temperature. Recent study also observed advanced maturity in 43 of the 44 studied winegrape blocks in Australian wine regons, and importantly a more rapid advancement during recent decades (Webb et al., 2011).

Winegrape phenology is likely to change under future climate changes in Australian wine regions. This was demonstrated by Webb et al. (2007) who examined six Australian wine regions and predicted earlier bud break (4 to 8 days by 2030 and 6 to 11 days by 2050) and a shortened growing season (45 days earlier harvest by 2050 in the Coonawarra region) in some wine regions of Australia due to the changing climate. In this study, the Margaret River region is modelled to have later bud breakt due to insufficient chilling temperature (Webb et al., 2007).

Australian premium winegrape varieties vary in their sensitivities to climate change (Webb et al., 2008b). Based on the above relationships Webb et al. (2008a) explored future climate change impacts on the Australian wine industry and concluded that, without adaptive measures, winegrape quality in Australia might be reduced, especially in inland regions, by up to 39% by 2030. This prediction is similar to projections for wine quality in Europe (Jones et al., 2005).

A study by Hall and Jones (2009) looked at potential impacts of future warming on Australian wine growing regions through spatial modelling and mapping of temperature-based indices under climate change. According to this research the number of wine growing regions with an increased median growing season temperature exceeding that for quality wine production, will increase by 8 by 2030, by 12 by 2050, and by 21 by 2070 implying a potential overall decrease in wine quality for the Australian wine industry under climate change (Hall and Jones, 2009).

### 2.3 Implications of potential climate change for viticulture

Variations in historical climate have produced changes in agricultural systems, including wine production in the past (Granger, 1980, Landsteiner, 1999, Jones and Davis, 2000b, Nemani et al., 2001). These variations include reduced frost occurrence, warmer temperatures and hence altered growing season lengths. Although there are uncertainties about future climate and the rate of change in a given region, it is now commonly acknowledged that future changes in climate are inevitable due to already emitted greenhouse gas in the Earth's atmosphere (Le Treut et al., 2007). The full impacts of future climate change on viticulture such as temperature and precipitation changes, elevated $CO_2$ levels and their interactions are not known.

Results of research studies suggest that climate change is likely to result in a shortened grape growing season and reduced fruit and wine quality for the currently cultivated varieties around the world (Hayhoe et al., 2004, Jones et al., 2005). Meanwhile, grape yield variation may increase due to the changing climate, indicating possible economic risk to grape growers (Bindi et al., 1996). Moreover, it is also argued that the future climate changes may have serious negative impacts on the suitability of currently planted varieties across current viticultural regions (White et al., 2006, Hall and Jones, 2009). Results of studies of climate change impacts on Australian viticulture indicate that future climate change may shorten the winegrape growing season and decrease winegrape quality if no adaptive strategies are implemented (Webb et al., 2007, Webb et al., 2008a).

From experience, it is known that climate extreme events affect crops more severely than mean values and their frequency of occurrence is highly correlated with changes in crop attributes (Katz and Brown, 1992). Climate extremes in Australia, such as drought, extreme high temperature and storms cause devastating damage on agricultural crops, albeit the frequencies of these events are low in the present climate. The projected increase in the frequencies of extreme climate events, however, raises the risk factors from these events. For viticulture, extreme climate events of interest in Australia might be extremely hot days with temperatures exceeding the levels of winegrape tolerance to heat; or a prolonged number of dry days with insufficient precipitation (Hayman et al., 2009, Webb et al., 2010); or too warm winters where winegrapes cannot get enough chilling for bud development (Lyons and Considine, 2007), resulting in lower fruit yield.

Most of the future climate impact assessment in this review, especially spatial modelling studies, focused on large areas of a global or national scale due to the availability of climate model outputs for simulation. Thus, to date research results do not give a detailed assessment of climate change impacts on viticulture at a regional or local level, which is important for grape growers to make decisions for their future business in response to climate changes.

## 2.4 Research methodology of this thesis

### 2.4.1 General workflow of the research

To achieve the overall objectives of this study we took the following steps (Figure 2.1). The study was sequential and linear with each step reliant on the findings of the previous one.

Step 1. Aimed at developing a background and understanding of the subject and delineation of the project aims. The step included the review of available information and discussion with industry and research personnel in this field. The formal research proposal was formulated at the end of this step.

Step 2. Ten sites were selected over a wide range of growing season average temperature. At each site maturity was monitored during two consequitive growing seasons and at maturity grapes were sampled and assessed for analysis of quality. Weather conditions were monitored at each site to enable comparison with quality and maturity observations.

Step 3. This step aimed at understanding the relationships between grape quality and climate data among the study regions. Empirical models of grape quality and climate data were developed through a multiple regression approach.

Step 4. This step produced finer scale spatial resolution climate change projections for the study area. This step was achieved by collaborating with the CSIRO Marine and Atmospheric Research Group project activities. Daily maximum and daily minimum temperatures, and daily rainfall data was generated for 10 GCM covering the area. Daily vapour pressure and radiation data were also generated.

Step 5. The purpose of this step was to determine the future climate characteristics of WA wine growing regions under climate change using the results of previous step. Downscaled climate data were converted into Geographic Information Systems (GIS) for spatial analysis.

Step 6. With this step, the aim was to determine the response of grape quality attributes to climate change for the wine regions within the study area. Results of the Step 1 and Step 2 were utilized for this step. Cabernet Sauvignon, Shiraz, and Chardonnay grape quality surfaces were constructed for future climate scenarios and examined with GIS spatial analysis tools.

Step 7. Overall findings of this research are discussed in relation to the general aim of this study. Shortcomings of this study are addressed and the future research directions are identified.

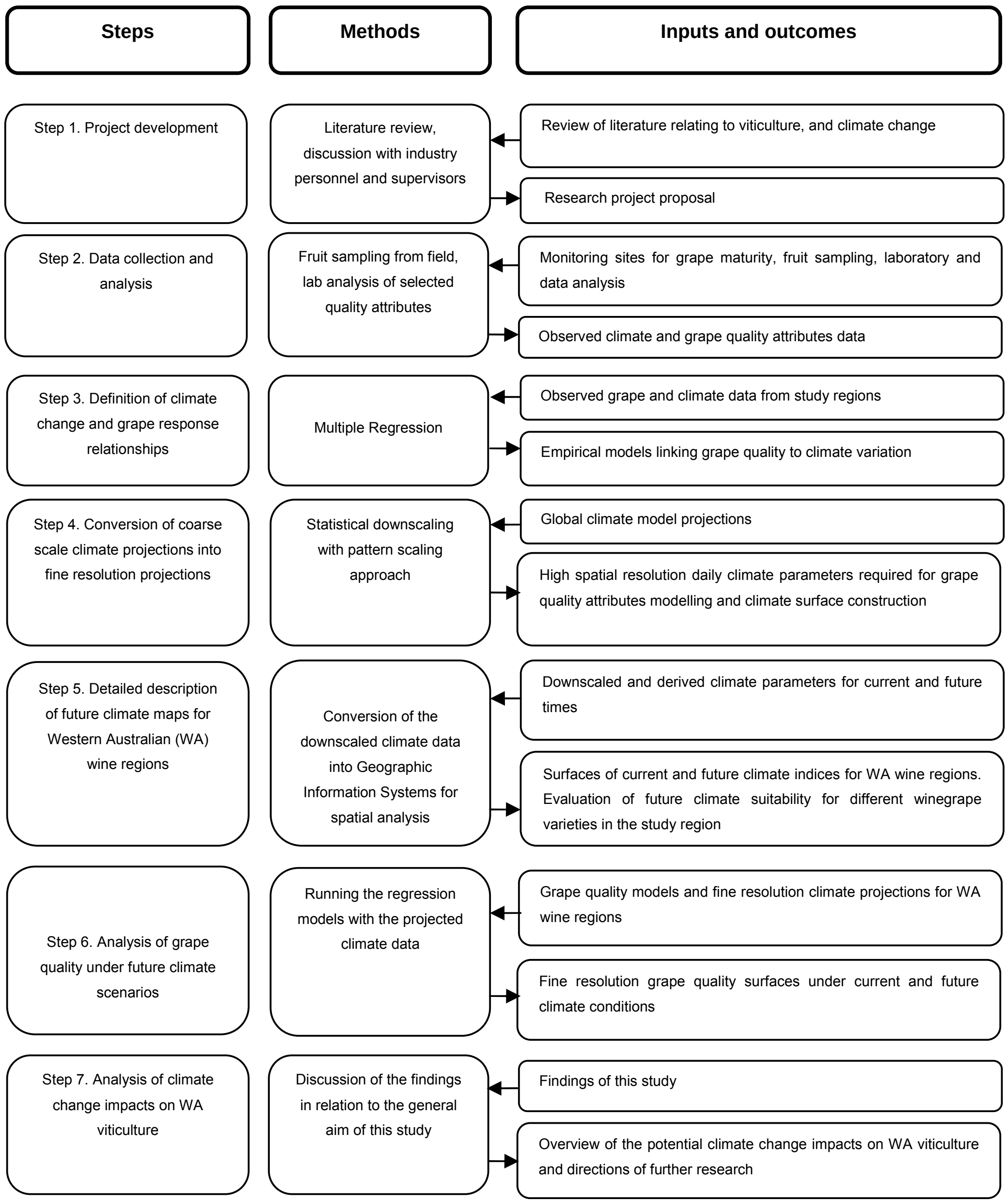


Figure 2.1 Workflow diagram showing major steps, methods, inputs and outputs utilised by the study

# CHAPTER 3. GRAPE QUALITY MODELLING

## 3.1 Introduction

Quality of grape berries and of the subsequent wine are strongly influenced by chemical constituents and their concentrations at harvest (Coombe et al., 1980, Herderich and Smith, 2005, Fontoin et al., 2008). Berry composition is influenced by factors such as climate, genotype, management and soil type (Gladstones, 1992, Jackson and Lombard, 1993). When other factors are held comparatively constant, climate is the dominant factor that influences grape and wine quality (Jones and Storchmann, 2001, Storchmann, 2005, Ashenfelter, 2008, Makra et al., 2009). Of the climate variables, temperature has been recognized as a primary driver of vine growth and grape/wine quality (Winkler, 1974, Gladstones, 1992, Soar et al., 2008). For example, Petrie and Sadras (2008) utilized between-season variation to demonstrate that higher growing season temperature resulted in increased rates of sugar accumulation and advanced fruit maturity dates. Furthermore, Sadras et al. (2007a) demonstrated negative relationships between the rate of the historical increases of red wine quality (as assessed by vintage scores) during 1980 to 2005 for Australian wine regions and average temperatures during the month before harvest.

Viticulture is a vulnerable sector to climate change due to the sensitivity of winegrape phenology and fruit quality to temperature. However, impacts of climate warming on viticulture remain unclear as the research results that are based on historical data generate various results. For example, Nemani et al. (2001) speculated that while climate warming during the period from 1965 to 1996 had positive effects on yield and wine quality in the Sonoma and Napa valleys, further warming may have unfavourable impacts on the Californian wine industry due to the increase in fungal disease under elevated temperature and humidity. Similarly, Lobel et al. (2006) indicated, based on predictions that used empirical yield and climate modeling, potential yield loss of perennial crops in California. On the other hand, Jones et al. (2005) explored the relationships between optimum growing season temperature and vintage score i.e. surrogate wine quality, and predicted uneven impacts of climate change on wine quality across the world's wine regions depending on current growing season temperature and future warming.

Australian studies generally suggest a consistently negative impact of climate change. For example, a study that broadly examined six Australian wine regions predicted a shortened growing season in all regions (Webb et al., 2007). According to this study, all regions, except Margaret River, are predicted to have earlier bud break and harvest dates in coming decades. Webb et al. (2008a, 2008b) also argued that there was likely to be variation in the sensitivity to climate change among winegrape varieties but that without adaptive measures winegrape quality in Australia will generally decrease. A more recent study (Hall and Jones, 2009) concluded that the number of current wine growing regions, with unsuitable growing season temperature for quality wine production, will increase as a result of climate change.

Plant growth and development are influenced by both absolute values and interactions among different climate variables. Therefore, inferences derived from relationships between an individual climate variable and grape quality parameter may not necessarily be the same when effects of other climate variables are taken together under real conditions. Plant physiological and mechanistic models, such as VineLogic (Godwin et al., 2002), would help to address such interactions provided the models have an adequate choice of inputs to simulate the whole system. However, to our knowledge, currently there are no readily available mechanistically parameterized models for simulating grape quality responses under climate change scenarios. Instead, empirical models have been used to investigate climate influences on grape growth and development and/or for evaluating the climate change impacts on viticulture (Jones and Davis, 2000a, Lobell et al., 2006, Ashenfelter, 2008). For this study, we employed an empirical modelling approach to examine the combined effects multiple climate variables on berry quality attributes.

To date all studies that have attempted to evaluate effects of climate change on grape and/or wine quality relied on proxy measures such as grape price (Webb et al., 2008a) or vintage scores (Jones et al., 2005, Sadras et al., 2007a). While these studies are valuable in providing a generalized picture, the observation that different grape varieties exhibit differential sensitivity to climate means that generalized projections based on indirect measures have limited value in predicting responses of specific varieties. Obviously, the underlying reason for using proxy variables as quality indicators is the absence of directly measured grape quality attribute data on responses of some of the major winegrape varieties to climate change. The work reported here was designed to fill this critical gap. Such data will be crucial in adaptation strategies – e.g., in decision making with regard to matching varieties with sites. The main aims of this work were to:

1. Determine responses of some key berry quality attributes (anthocyanins, titratable acidity and pH) to range of baseline climates, and
2. Develop quantitative (empirical) models that could be used for assessing levels of these berry quality attributes to the projected climate change across the major viticultural areas of Western Australia.

The study was carried out in commercial vineyards located along natural gradients of climate, and covered three of the major winegrape varieties (Cabernet Sauvignon, Shiraz and Chardonnay) currently grown in Australia.

## 3.2 Materials and methods

### 3.2.1 Monitoring sites and plant material

Ten commercial vineyards situated in all the major wine regions of Western Australia (Figure 3.1) were used for this study to monitor the dynamics of Titratable Acidity (TA), pH and total anthocyanins in Cabernet Sauvignon, Shiraz and Chardonnay varieties. The monitoring was carried out from véraison to until berry juice Total Soluble Solids (TSS) level reaches 22 °Brix during the 2008-2009 (Season 1, hereafter) and 2009-2010 (Season 2, hereafter) growing seasons. The 10 study vineyards lie along a north-south transect with an average (1976-2005) growing season temperature (October to April) that ranged from 17.8$^{o}$C at the southern most site to 22.9$^{o}$C at the northern most vineyard site.

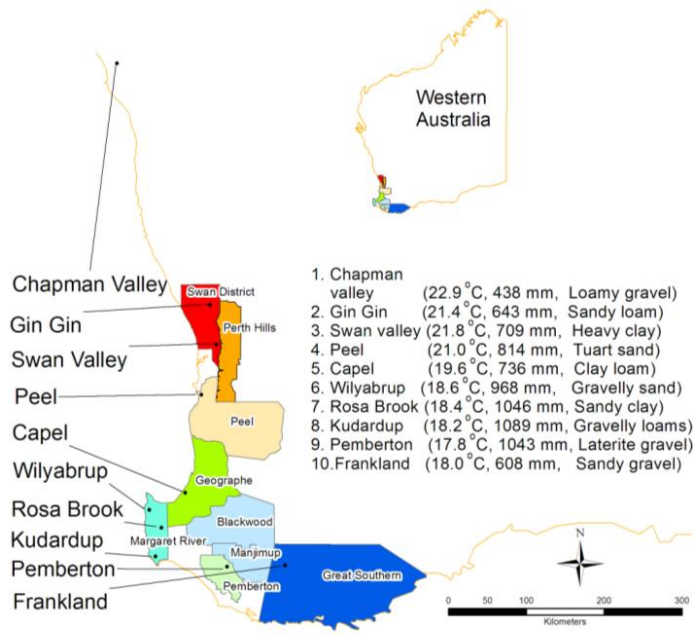


Figure 3.1 Map sampling site locations and their long term climate averages. October to April average temperature, average annual rainfall, and dominant soil types for each site are indicated in bracket. Climate data is averaged for 1976 to 2005 period from SILO DataDrill database, respectively

It is acknowledged that different vineyard management practices and properties of plant material among different sites can contribute to variations in fruit quality attributes. However, it was not feasible to utilise monitoring sites with identical planting material and management practices along the entire transect. Most of the sites in this study had vertical shoot positioning (VSP) training and spur pruning, except Capel, Willyabrup (both had T-trellis) and Frankland (bilateral) sites. Similarly, the varieties were mainly planted on their own-roots except Chardonnay at Gin Gin (which was grafted onto Chenin Blanc), Shiraz and Chardonnay (on Schwarzmann) at Swan Valley and Cabernet Sauvignon and Chardonnay (on Schwarzmann) at Pemberton. The vines were between 5 and 25 years old (Table 3.1). The soil types also varied across sites (Figure 3.1).

Table 3.1 Vine ages and training systems for the study sites

| Sites | Shiraz | | Cabernet Sauvignon | | Chardonnay | |
|---|---|---|---|---|---|---|
| | Age (years) | Training | Age (years) | Training | Age (years) | Training |
| Chapman Valley | 10 | VSP | 10 | VSP | | |
| Gin Gin | 5 | VSP | 5 | VSP | 5 | VSP |
| Swan Valley | 20 | VSP | | | 5 | VSP |
| Peel | 25 | VSP | 25 | VSP | 25 | VSP |
| Capel | 20 | T-trellis | 20 | T-trellis | 20 | T-Trellis |
| Wilyabrup | Not known | VSP | Not known | T-trellis | Not known | VSP |
| Rosa Brook | 11 | VSP | 14 | VSP, spur | 11 | VSP |
| Kudardup | | | 8 | VSP, spur | 8 | VSP |
| Frankland | 10 | Bi-lateral | 10 | Bi-lateral | 10 | Bi-lateral |
| Pemberton | 11 | VSP | 17 | VSP | 18 | VSP, spur |

Blank cells indicate that the particular variety is not available on that vineyard for sampling. VSP- Vertical shoot positioning

### 3.2.2 Bunch sampling

Ten bunches of grapes from 10 vines, five from one side of a row and the others from the opposite side of the row, were randomly sampled for each variety at weekly intervals between the start of véraison and the berry TSS maturity of 22 $^{o}$Brix (referred to as common maturity, hereafter). The 10 sample vines were selected from four rows in the middle of a block to avoid edge effects and in such a way that no vines are sampled twice during the sampling period (Figure 3.2). Sampled bunches were placed in an ice chilled box and taken to the laboratory for berry composition analysis.

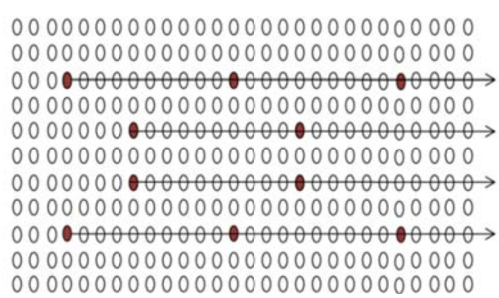

Figure 3.2 Sampling design illustration. Shaded ovals indicate positions of the first sampled vines in a row and vines in the same row along the arrow are sampled subsequently in each week

3.2.3 Berry composition analysis

A quarter of the berries were evenly and gently stripped from all parts of the sampled bunches. Half of the berries were placed in a plastic bag and crushed by hand without cracking the seeds and the juice was used for TSS, pH and TA analysis. The remaining berries were placed in a plastic container and kept frozen for anthocyanin analysis. Juice from the hand-crushed berries was centrifuged (HeraEus Multifuge 3SR+, USA) at 3500 rpm for 10 minutes. Levels of TSS were measured with a temperature compensated digital refractometer (Reichert AR200, USA) and reported in $^{o}$Brix at 20 $^{o}$C. Juice pH and TA were measured with a pH meter (labCHEM-pH, Australia) from the centrifuged juice. Titratable acidity was determined by titrating juice samples against 0.1 kmol $m^{-3}$ NaOH solution to an end point of pH 8.2. Results are expressed as grams of tartaric acid equivalent per litre of juice (g/L).

Anthocyanins were extracted and analysed as described in Iland et al. (2004). Briefly, after thawing frozen samples, 50 berries were randomly selected and weighed. These were homogenized (Ultra Turrax T25 Basic, Germany) at 24000 rpm until the sample became a smooth paste. Approximately 1 g of the homogenate was weighed into a centrifuge tube and 10 ml of 50% aqueous ethanol (pH 2) was added. The homogenate-ethanol mixture was agitated continuously for 10 minutes to facilitate extraction of anthocyanins. The samples were then centrifuged at 3500 rpm for 5 minutes. A subsample of the supernatant was diluted 1:10 with 1 kmol $m^{-3}$ HCl. After 3 hours, absorbance values of the diluted samples were recorded at 520 nm with a spectrophotometer (UV-2450, Shimadzu, Japan). Anthocyanin concentration results are expressed as mg malvidin-3-glucoside equivalents per g berry weight (mg/g).

### 3.2.4 Climate data

Temperature was measured at 15 minute interval during the post véraison to harvest period (shielded Tinytag TG-0050, Gemini Data Loggers Ltd., UK) at each site. All loggers were tested for their accuracy prior to their deployment at sites. The loggers were placed in plastic shielding screens to protect from direct radiation or rainfall and hung from the top wires between poles in the middle of the sampling blocks. Growing shoots within a half meter in both sides of the screen were regularly removed to prevent shading. In addition, daily climate data for each site was obtained from the SILO data drill database (Jeffrey et al., 2001) for other climate variables such rainfall, radiation, and moisture. The logged temperature data were used for estimating the length of time over certain temperature, whereas the interpolated climate data i.e. temperature, rain, radiation etc. were used for model development for consistency. The logged and interpolated data were verified against each other for each site (Appendix 1) prior to the analyses.

Climate variables for growing season and véraison periods were calculated separately for each variety and season since the growing season lengths were different for each variety and/or season. For this study, the growing season was defined as the period between 1st of October and the date when fruit reached the common maturity. Ripening period and véraison periods were defined as the 30 day period preceding the common maturity and the period between the beginning of véraison (50% of the fruit reaches veraison) and the common maturity date, respectively.

### 3.2.5 Data standardisation

Due to the weekly sampling interval some samples were not taken at a TSS of exact 22 °Brix (common maturity) on the sampling dates. For this reason, a linear interpolation was carried out to estimate the quality parameter for those samples whose TSS values varied by more than 0.2 °Brix from the common maturity. The common maturity is interpolated from a linear regression between accumulated biologically effective degree days (Gladstones, 1992) (difference between the daily average temperature capped at 19°C and base of 10°C) and the TSS values of two consecutive samples that contained the targeted common maturity. Overall, the variation between the interpolated common maturity TSS and actual values across sites and varieties differed by less than 0.6 $^{o}$Brix units. Similarly, the pH, TA and anthocyanins at the common maturity were calculated from linear regressions between TSS and the quality parameters.

### 3.2.6 Selection of climate variables

While temperature, rainfall and radiation are the essential and basic components of climate that affect plant growth and development, variables derived from these basic components of climate may also influence berry quality. Thus, *a priori* list of basic climate variables and derivatives thereof that potentially affect berry quality was compiled (Table 3.2), and their values computed for the entire or specific periods of the growing season. This exercise generated more than 70 variables (Table 3.2, Figure 3.4). Durations (h) over 25°C and 30°C during fruit ripening were estimated from the logged temperature on vineyard sites. In warmer sites, grapes reached the common maturity in February; hence climate variables beyond this time were not included in the analyses reported here. Thus, although the growing season for the Southern Hemisphere is nominally defined from October to April, in this work the growing season ranges from October to the time grapes reached the common maturity.

### 3.2.7 Data analysis

Relationships of grape quality attributes to climate variables were explored through correlation and simple (multiple) linear regression analyses. The number of basic and derived climate (independent) variables was 3 to 4 times the number of berry quality observations (dependent variables). Considering these small sample sizes, the maximum number of independent variables in the multiple regression analyses was capped at three (using a start with one independent variable and stop with three variables selection and switching routine).

Table 3.2 Climate variables used for investigating grape fruit quality attributes at maturity

| Climate variables | Climate variables that had been used previously and reference | Additional variables used for this study |
|---|---|---|
| Temperature | Mean January temperature (Smart and Dry, 1980; Webb et al., 2008a), Spring temperatures up to flowering (Keller et al., 2010) | October to February monthly minimum, maximum, and average temperatures (°C) |
| | Growing season average temperature (Ashenfelter, 2008; Jones et al., 2005) | Growing season† (GS) minimum, average, and maximum temperatures |
| | Temperature during fruit maturity (Sadras et al., 2007a; Storchmann, 2005) | Minimum, maximum, and average temperatures during Ripening period‡ (RP)<br>Number of hours over 25°C during RP |
| | Degree days. (Sum of daily mean temperature over 10°C during grape growing season) | Growing degree days (GDD) during growing season |
| | Number of days with maximum temperature over 25°C during GS (Jones and Davis, 2000a) | Number of days with maximum temperature over 25°C during GS, and RP (in days) |
| | Diurnal range (DR) (Gladstones, 1992; Nemani et al., 2001) | Monthly DR between December to February, GS, RP, Véraison period§, and for period between October to February |
| Moisture condition | Rainfall (mm) (Gladstones, 1992) | Amount of rainfall for early (September to November) and for whole GS |
| | Moisture stress (Chalmers et al., 2010; Gladstones, 1992) | Daily mean Evaporation between October to February months, and RP (in mm)<br>Mean daily Vapour pressure deficit (VPD) for October to February months, and for RP |
| | Soil water holding capacity (Jackson, 2000, Sivilotti et al., 2005) | Available soil water holding capacity in top 2 A and B soil layers |
| Radiation | Radiation (Ristic et al., 2007, Gladstones, 1992) | Mean daily radiation between October to February months, and for RP |

†Growing season = period between October and the date when the fruits reach 22 °Brix of Total soluble solids (TSS) maturity (common maturity), ‡Ripening period = 30 day period preceding the common maturity, §Véraison period = period between starting of véraison and the common maturity

Even with this restriction, however, several thousand candidate models are generated for each variety. Selection of the likely models for the given data among these candidate models was carried out using Akaike Information Criterion corrected for small sample size (AICc) (Burnham and Anderson, 2002). Of the candidate models, the model with the minimum AICc and others whose AICc was within 5 units of the minimum AICc model were retained for further examination of model results against some known biology of the reality being modelled.

Model selection based on traditional methods (adjusted $r^2$, Mallows' $C_p$, and predicted residual sum of squares) was carried out in addition to the information theory approach. The climate variables used for model building generally had a high degree of correlation. This often causes high multicollinearity which is manifest, among others, in the form of high variance inflation factors (VIF) of parameter estimates and high condition numbers. Thus, the selected models were further screened with rule-of-thumb guidelines of 10 for VIF and 1000 for condition number (e.g. (Myers, 1986)). When a combination of climate variables appeared to account for a very large proportion of the observed variance (e.g., > 97%) in berry quality while exhibiting severe multicollinearity, ridge regression was performed on such variables. However, it was often the case that at the ridge step that stabilised parameter estimates (VIF ~ 1), the penalised ridge model no longer retained its high explanatory power. In such cases, the variables and/or models were excluded from the results presented here despite the apparently high descriptive power of the initial models. Finally, for the data under consideration, 1 or 2 most probable models were presented and discussed for each attribute per variety (variety-specific models) or each attribute across varieties (generic models). All analyses were carried out with SAS v 9.1 (SAS Institute Inc., Cary, NC, USA).

## 3.3 Results

### 3.3.1 Growing season temperature and rainfall during the study period

October to March average temperature differences between the warmest and coolest sites were over 5°C for both seasons (Table 3.3). There were also considerable differences in rainfall (10-fold in Season 1 and 3-fold in Season 2). However, the grape ripening periods were virtually rain free, and all sites used supplementary irrigation.

Table 3.3 October to March average temperature and rainfall across the study sites during Season 1 (2008-2009), and Season 2 (2009-2010)

| | October to March average temperature (°C) | | October to March rainfall (mm) | |
|---|---|---|---|---|
| Sites | 2008-2009 | 2009-2010 | 2008-2009 | 2009-2010 |
| Chapman Valley | 23.1 | 24.2 | 35 | 52 |
| Gin Gin | 21.5 | | 96 | |
| Swan Valley | 21.9 | 23.2 | 124 | 88 |
| Peel | 21.0 | 22.2 | 161 | 78 |
| Capel | 19.6 | 20.5 | 94 | 65 |
| Wilyabrup | 18.7 | 19.1 | 161 | 95 |
| Rosa Brook | 18.2 | 18.9 | 140 | 96 |
| Kudardup | 18.1 | 18.6 | 239 | 95 |
| Frankland | 17.9 | | 219 | |
| Pemberton | 17.7 | 18.8 | 363 | 154 |

Data source; Interpolated (SILO DataDrill Database) weather data

### 3.3.2 Patterns of berry quality attributes at common maturity across sites

At common maturity, there were significant differences in the levels of grape quality attributes between the cooler and warmer sites. Generally, berries from the cooler sites, for instance Frankland and Pemberton, had higher levels of anthocyanins (48 to 71% for Cabernet Sauvignon and 22 to 30% for Shiraz, depending on the season) than those from the warmer sites, such as the Swan or the Chapman Valleys (Figure 3.3). Likewise, the levels of TA were higher in cooler sites: 31 to 62% for Cabernet Sauvignon, 32 to 82% for Shiraz, and 61 to 126% higher for Chardonnay depending on season (Figure 3.3). Unlike the anthocyanins and TA levels, grape juice pH at common maturity did not show a clear trend across sites when the sites were characterized by the long term growing season average temperature alone (Figure 3.3). Nonetheless, the highest juice pH levels were observed at the warmer sites in both seasons (Chapman Valley for Shiraz and Cabernet Sauvignon, and at the Swan Valley for Chardonnay).

### 3.3.3 Relationships of berry quality attributes with climate variables

Exploratory bivariate correlation analyses of climate variables at different time periods during the growing season and grape quality attributes at common maturity identified climate variables and critical time periods that were influential on grape quality. These are detailed below.

#### 3.3.3.1 Titratable acidity at common maturity and climate

Rainfall either early in the growing season (September to November) or during the entire growing season had positive impacts on TA levels at common maturity (Figure 3.4a). Available soil water holding capacity (AWC) generally appeared to have little influence on TA at common maturity. By contrast, for all three varieties, TA levels at common maturity were negatively related to temperature (and the temperature-derived variables), radiation and evaporation (Figure 3.4a).

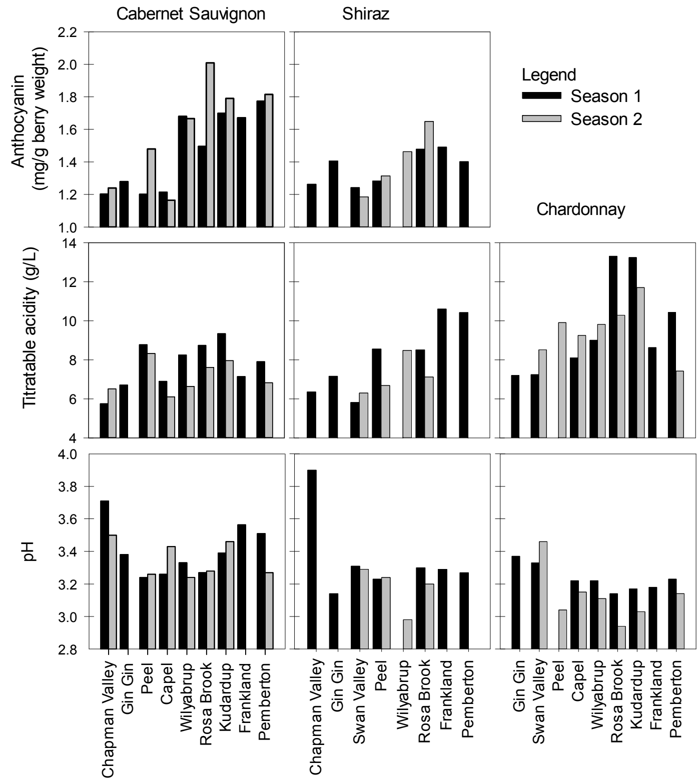


Figure 3.3 Levels of grape quality attributes (anthocyanins, Titratable acidity, and pH) at common maturity (TSS of 22 °Brix). Sites are listed (from left to right) according their long term growing season temperature in decreasing order

In particular, consistently strong negative correlations (*R*~ -0.47 to -0.82) were observed with variables involving maximum temperature and its derivatives such as diurnal temperature range and VPD during December, January and February; frequency of days above 25 $^{o}$C during the growing season, and the number of hours over 30 $^{o}$C during the ripening period. Correlations of TA at common maturity with minimum temperatures early in the growing season were both weak and varied among varieties; however, the strength of correlations steadily increased and became qualitatively similar as the season progressed, becoming strongest during the ripening period (Figure 3.4a). Such steady increases in the correlation strength from October to January/February months were also evident for the other monthly average climate variables (Figure 3.4a), thus confirming the relative importance of climate during berry maturity for berry composition (see also results for pH and anthocyanins below).

### 3.3.3.2 pH at common maturity and climate

The bivariate correlations of juice pH at common maturity with all climate variables were: (1) opposite of the TA results, and (2) of generally lower strength than the TA correlatons with climate variables (*c.f.* Figure 3.4a and 3.4b). While the strongest pH correlations were observed with climate variables for the month of February and, unexpectedly, October (Figure 3.4b), the correlations showed dynamic temporal patterns. Thus, in general, pH correlations with temperature, diurnal range and Vapour Pressure Deficit (VPD) variables started with a peak in October, attained a minimum in November and steadily rose back to peak level in February; correlations with evaporation and radiation variables also started with a peak in October, declined until December and returned back to a peak level in February (Figure 3.4b).

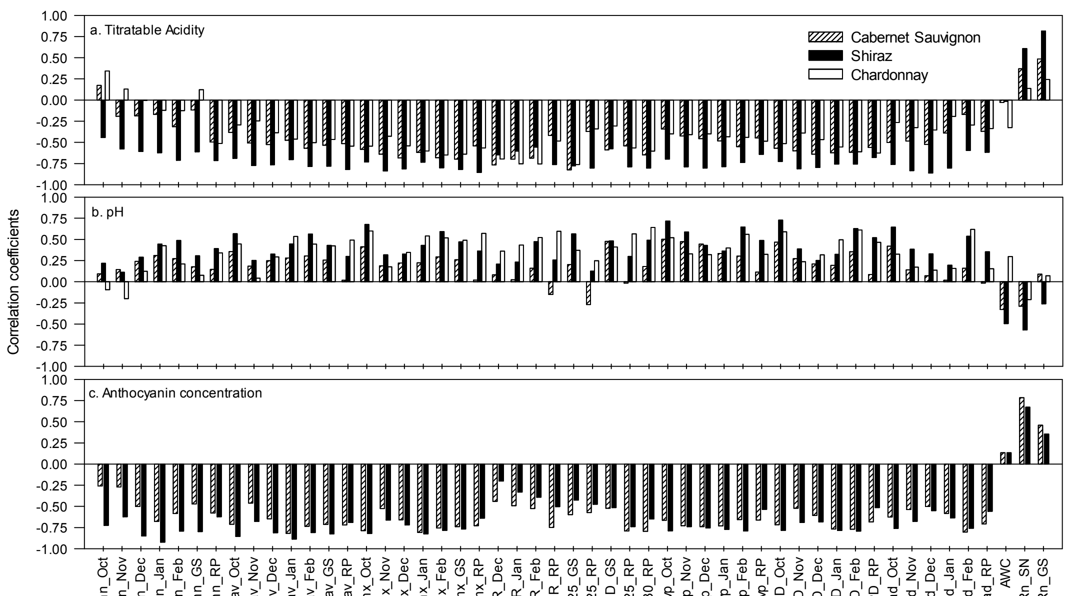


Figure 3.4. Correlations between grape quality attributes (Titratable acidity, pH, anthocyanin concentrations) at common maturity (TSS= 22 °Brix) and climate variables for Cabernet Sauvignon, Shiraz and Chardonnay. Tmn, Tav, Tmx= minimum, average, and maximum temperatures respectively, months are denoted by their initial three letters, RP=ripening period, DR=diurnal range, D25 or D30=number of days with maximum temperature over 25°C or 30°C, H25 or H30=number of hours over 25°C or 30°C, Evp=evaporation, VPD=vapour pressure deficit, Rad=net radiation, AWC=available soil water holding capacity, Rn_SN or Rn_GS=rainfall during September to November or during growing season, respectively

#### 3.3.3.3 Anthocyanin concentrations and climate

For both Shiraz and Cabernet Sauvignon, berry anthocyanin concentrations at common maturity were negatively associated with almost all the climate variables examined in this study (Figure. 3.4c). Only rainfall variables had positive influences on the anthocyanin concentration. Of rainfall, rainfall incident early in the growing season (September to November) appeared to have a stronger influence on berry anthocyanins than rainfall during the whole growing season.

Similar to the results for pH, berry anthocyanin concentrations of both red wine varieties were highly correlated ($R$~ -0.78 to -0.82) with October temperatures, particularly the average and maximum temperatures (Figure 3.4c). The strengths of correlations with November temperatures showed a slight drop, from there on however, the influences of temperatures on berry anthocyanin concentration steadily increased up to January/February (ripening months) (Figure. 3.4c). This temporal pattern was common across the minimum, average and maximum temperatures. Similarly, the degree of association between berry anthocyanin concentration at common maturity with diurnal range variables, while generally moderate during December ($R$~ -0.20 to -0.40), became stronger ($R$~ -0.50 to -0.75) towards the ripening period, further affirming the importance of climate during ripening for berry composition. Other variables that appeared to exert relatively strong negative influence, ($R < -0.7$) on berry anthocyanin concentrations of both varieties were the number of hours that the air temperature exceeded 25°C during the ripening period, VPD during January/February and radiation in February. For most of the growing season berry anthocyanin concentration also had a strong negative association with evaporative demand (Figure 3.4c).

### 3.3.3.4 Temperature effects on rates of change of berry anthocyanin concentrations, TA and pH

For both red wine varieties, berry anthocyanin concentrations were significant and inversely related to the average temperature of the véraison period. However, the rate of decline, expressed as the slope of the linear regression, in anthocyanin concentrations per degree increase in the véraison period average temperature was significantly greater for Cabernet Sauvignon (0.07 mg/g per degree °C increase) than for Shiraz (0.03 mg/g per degree °C increase) (Figure 3.5). Similarly, for all three varieties, the levels of TA at common maturity declined significantly as a site's growing season average daily maximum temperature increased (Figure 3.6a). The rate of acid loss however varied considerably with variety, with Cabernet Sauvignon and Chardonnay being the least and most sensitive, respectively (Figure 3.6a). In contrast to the responses of anthocyanin and TA, berry juice pH levels for all varieties showed positive trends with the growing season average daily maximum temperature, though these were not significant ($p$ > 0.05) (Figure 3.6b).

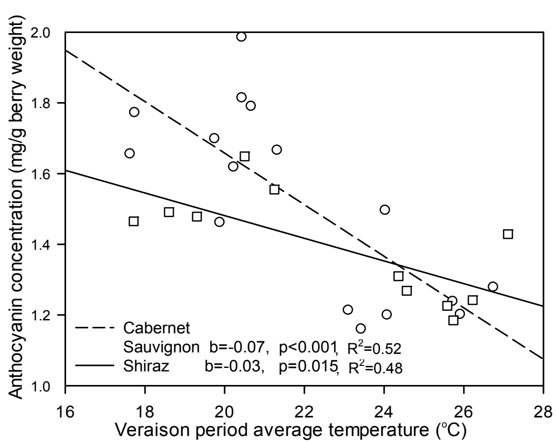


Figure 3.5 Relationships between berry anthocyanin concentrations at common total soluble solids maturity (22 °Brix) and véraison period average temperatures for Cabernet Sauvignon (circles), Shiraz (squares) varieties. Data points represent different sites. b = slope of the regression, p = significance value

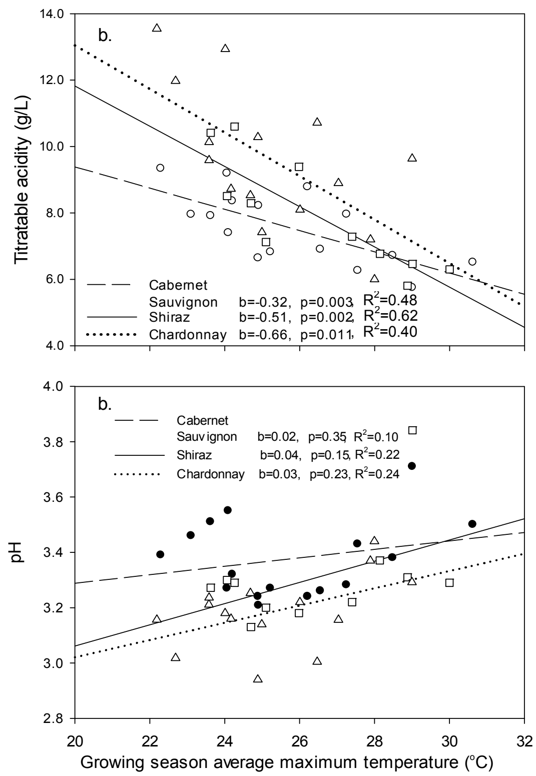


Figure 3.6 Relationships between berry (a) titratable acidity, and (b) pH levels at common maturity (total soluble solid of 22 °Brix) and growing season maximum temperatures for Cabernet Sauvignon (circles), Shiraz (squares) and Chardonnay (triangles) varieties. Data points represent sites. b = slope of the regression, p = significance value

### 3.3.3.5 Ripening period temperature effects on dynamics of anthocyanin accumulation and TA vis-à-vis TSS

For all three varieties, the rates of change in TA per unit increase in TSS during véraison were negatively related to the sites' prevailing average temperature (Figure 3.7a). However, the trend was significant ($p$ < 0.05) for Chardonnay only, while the trends for Cabernet Sauvignon and Shiraz were marginal ($p$ = 0.053 and $p$=0.112, respectively). On the whole, these results suggest accelerated loss of acid per °Brix increase in TSS at warmer sites compared to cooler sites during berry ripening.

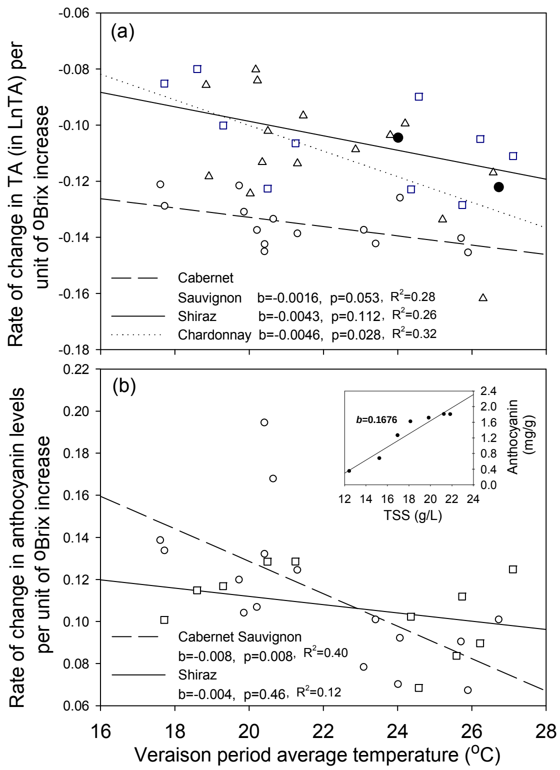


Figure 3.7 Relationships between véraison period average temperature and rate of changes in (a) titratable acidity, or (b) anthocyanin concentration per unit of TSS increase for Cabernet Sauvignon (circles), Shiraz (squares), and Chardonnay (triangles) varieties. Two extreme values of (shaded circles) Cabernet Sauvignon titratable acidity decrease rate are not included in the regression. Estimation of the change rate of quality attributes over the véraison to harvest is illustrated in the inset using sequential sampling data from the Kudardup site in the Season 2 véraison period

Similarly to the TA responses, for both Shiraz and Cabernet Sauvignon, the rates of change in anthocyanin concentration per unit TSS increase trended negatively as the véraison period average temperature increased (Figure 3.7b). However, there were apparent varietal differences in the strength of this relationship, with the trend being significant for Cabernet Sauvignon only. Thus, for Cabernet Sauvignon these data suggest that relative to sugar accumulation, net anthocyanin accumulation progresses slowly in environments with warmer ripening periods whereas for Shiraz, the relative rates appeared less sensitive.

### 3.3.4 Empirical models of berry quality responses to changing climate conditions

#### 3.3.4.1 Anthocyanin concentration

Out of more than 70 basic and derived climate variables, only a few (mean January temperature, radiation and number of hours over 25°C during the berry ripening periond, and rainfall both during the September to November period, and the whole growing season) were pertinent for describing the variations in berry anthocyanin concentrations at common maturity along the 700 km sampling transect covering all the viticultural regions of Western Australia (Table 3.4).

A three-variable generic model consisting of rainfall during spring, the growing season and the number of hours that the air temperature exceeded 25 $^{o}$C during the berry ripening period explained >70% of the variation in berry anthocyanin concentrations at maturity for both varieties (Table 3.4). The effects of these three variables on berry anthocyanins were in the same direction as their individual effects (*c.f.* Figure. 3.4c, Table 3.4). Accordingly, duration of air temperature above 25 $^{o}$C during berry ripening had a negative influence on anthocyanin concentrations. The effects of rainfall however were dependent on when it occurred during the growing season. Thus, whilst rainfall early in the growing season (September to November) had a positive effect, rainfall over the entire growing season had an unfavourable effect on berry anthocyanin levels. Partitioning the total growing season rainfall into early and late season rainfall also produced qualitatively and quantitatively comparable effects on berry anthocyanin concentrations.

Compared to the generic model result, high proportions of the variations in berry anthocyanins were accounted for by variety-specific models. For Cabernet Sauvignon, the same three variables used in the generic model explained 83% of the variablity in berry anthocyanin concentrations across the sampling transect (Table 3.4).

For Shiraz, a two-variable model of January minimum temperature and ripening period radiation described 70% of the variation in berry anthocyanins at maturity across sites. However, when one highly influential outlier observation was excluded, the proportion of variance explained by the same two variables increased to 94% (Table 3.4). It is noteworthy that, for both varieties, when a model contained both temperature and ripening period radiation, the radiation effect on anthocyanin concentrations was positive (i.e., contrary to the bivariate effect). Also notable was that, for both varieties, the minimum or average January temperature alone accounted for between 50 and 83% the variablity in berry anthocyanin concentrations (Table 3.4).

Although not tabulated, for Shiraz - a variety known for its propensity for berry shrivel – berry anthocyanin concentrations responded significantly and positively to vapour pressure deficit (VPD). (For example, *Anthocyanins* $_{(Shiraz)}$*= 3.78 + 0.035November VPD + 0.023 Ripening period VPD − 0.141 January to February average temperature,* $R^2$*_adj = 0.92; Anthocyanins* $_{(Shiraz)}$*=3.44 + 0.023 December VPD + 0.016 Ripening period VPD − 0.119 Mean January temperature ,* $R^2$*_adj = 0.89; all terms significant at* $p < 0.001$).

### 3.3.4.2 pH

Compared to anthocyanins and TA (see below), juice pH at common maturity was generally weakly associated with the climate variables examined in this study. Yet, several models appeared to describe high proportions (e.g., up to 97% for Shiraz) of the variances in pH along the sampling transect. However, the parameter estimates for one or more of the climate variables in the models were unreliable and all such models were excluded. After this screening, the “best” candidate was a generic model containing growing season growing degree days and October vapour pressure deficit which described only half of the pH variations along the climate gradient (Table 3.5). For both variables, the directions of influence on pH were same as their individual effects.

Table 3.4 Generic and variety specific model estimates for berry anthocyanin concentration (mg/g berry weight)

| | | Climate variables | | | | | | Model performance | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Variety | Intercept | Rn_SN | Rn_GS | Hr25_RP | Tav_Jan | Tmn_Jan | Rad_RP | Adj_$r^2$ | PRESS | $VIF_{max}$ |
| Generic model | 1.68***<br>(se 0.14)<br>(CI 1.32÷1.92) | 0.002***<br>(se 0.0004)<br>(CI 0.001÷ 0.003) | -0.002***<br>(se 0.0004)<br>( CI -0.003÷ 0.001) | -0.001***<br>(se 0.0003)<br>(CI -0.002÷ -0.001) | | | | 0.72 | 0.51 | 3.06 |
| Cabernet Sauvignon | 1.72***<br>(se 0.18)<br>(CI 1.30÷2.11) | 0.002***<br>(se 0.0005)<br>(CI -0.003÷ 0.003) | -0.002***<br>(se 0.0005)<br>(CI -0.003÷ -0.0008) | -0.002***<br>(se 0.0004)<br>(CI -0.0025÷ -0.001) | | | | 0.83 | 0.24 | 2.83 |
| | 3.63***<br>0.39<br>(CI 2.77 4.48) | | | | -0.094**<br>(se 0.02)<br>(CI -0.13÷ -0.05) | | | 0.65 | 0.44 | |
| Shiraz | §2.39***<br>(se 0.29)<br>CI 1.73÷3.0) | | | | -0.042**<br>(se 0.01)<br>(CI -0.007÷ -0.01) | | | 0.50 | 0.17 | |
| | §2.24***<br>(se 0.18)<br>(CI 1.82÷2.65) | | | | | -0.091**<br>(se 0.02)<br>(CI -0.13÷ -0.04) | 0.029*<br>(se 0.01)<br>(CI .003÷ 0.05) | 70.0 | 0.10 | 3.20 |
| | †2.38***<br>(se 0.08)<br>(CI 2.18÷2.57) | | | | | -0.091***<br>(se 0.008)<br>(CI -0.11÷ -0.07) | 0.022<br>(se 0.005)<br>(CI 0.01÷ 0.03) | 0.94 | 0.02 | 2.89 |
| | †2.40***<br>(se 0.14)<br>(CI 2.1÷2.71) | | | | | -0.061***<br>(se 0.008)<br>(CI -0.08÷ -0.04) | | 0.83 | 0.05 | |
| | †2.59***<br>(se 0.21)<br>(CI 2.11÷3.06) | | | | -0.051***<br>(se 0.009)<br>(CI -0.07÷ -0.03) | | | 0.77 | 0.07 | |

Significance; ** $p < 0.01$, *** $p < 0.001$, §based on all data, †excludes one outlier observation, se=standard error, CI=95% confidence interval, PRESS = predicted residual sum of squares, $VIF_{max}$ = maximum variance inflation factor, Rn_SN, Rn_GS = September to November months and Growing season rainfalls (mm), Hr25_RP = number of hours over 25°C during ripening period, Tav_Jan, Tmn_Jan = average and mean of minimum temperatures in January (°C), Rad_RP = radiation during ripening period ($MJ/m^2$)

Table 3.5 Generic model estimates for pH level

| | Climate variables | | Model performance | | |
|---|---|---|---|---|---|
| Intercept | GDD_GS | VPD_Oct | Adj_$r^2$ | PRESS | VIFmax |
| 2.06***<br>(se 0.22)<br>(CI 1.62÷2.5) | 0.00071 ***<br>(se 0.0002)<br>(CI 0.0004÷0.001) | 0.0021***<br>(0.007)<br>(0.006÷0.035) | 0.52 | 0.76 | 1.31 |

Significance; *$p < 0.05$, ** $p < 0.01$, *** $p < 0.001$, se=standard error, CI=95% confidence interval, PRESS = predicted residual sum of squares, VIFmax = maximum variance inflation factor, GDD_GS = growing season Growing degree days, VPD_Oct = October mean daily vapour pressure (kPa)

### 3.3.4.3 Titratable acidity

For all varieties, between 59% and 63% of the variations in berry TA levels at common maturity were described using generic models consisting of two temperature derived-variables: Growing season diurnal range (DR_GS) and Ripening period minimum temperature (Tmn_RP) or Growing season growing degree days (GDD_GS) and January diurnal range or GDD_GS and October to February diurnal range (Table 3.6). In all three generic models, the impacts of these temperature derivatives on TA were significant ($p < 0.001$) and negative (Table 3.6). That is, other factors being equal, increases in a site's growing degree days, diurnal range or Tmn_RP reduces berry TA at common maturity.

As evident for anthocyanin concentrations, variety-specific TA models explained significantly higher proportions of the variation in TA than were possible with the generic models (Table 3.6). Thus, for Cabernet Sauvignon, a model containing DR_GS and Tmn_RP accounted for about 77% of the variability in TA while a three-variable model with GDD_GS, DR_GS and Rn_GS (Growing season rainfall) explained 85% the TA variation at maturity along the climate gradient. Once more, the impacts of increases in all these variables, except Rn_GS, were manifest with a reduction of TA levels at common maturity, corroborating the inverse relationship between heat and TA levels. By contrast, the effect of increased rainfall, the other two factors were held constant, was to increase TA levels, indicating that increased moisture availability favours higher acidity at maturity.

For Chardonnay, the conjoint influences of DR_GS and Tmn_RP alone explained 81% of the TA variance at maturity. Two three-variable models: a) DR_Feb (February diurnal range), Tmn_RP, Rad_Oct (October radiation) and b) Tmn_RP, D25_GS (days with maximum temperature over 25°C during growing season) and Rad_Nov (November radiatiaon) accounted for slightly more of the variances across the climate gradient (Table 3.6). As observed for Cabernet, the effects of all the temperature-derived variables on TA were negative. It is noteworthy however that the direction of Rad_Oct impact on TA in this multivariate setting was contrary to the results from the bivariate case (Figure 3.4, Table 3.6).

In Shiraz, the maximum temperature during the ripening period alone explained 70% of the variation in TA at common maturity across the sampling transect. However, the best candidate model contained two-variables (October to February diurnal range and Rn_GS), which jointly accounted for 82% of the variation in Shiraz TA across the transect over two seasons. Consistent with the results for Chardonnay and Cabenet Sauvignon, the effects on TA of the temperature-based factors in the Shiraz models were negative while the impact of the rainfall term was positive (Table 3.6).

Table 3.6 Generic and variety specific model estimates for berry juice titratable acidity level (g/L)

| | | Climate variable | | | | | | | | | | | Model performance | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Variety** | **Intercept** | **GDD_GS** | **DR_GS** | **DR_OF** | **DR_Jan** | **DR_Feb** | **Rn_GS** | **Tmn_RP** | **Tmx_RP** | **D25_GS** | **Rad_Oct** | **Rad_Nov** | **Adj_r$^2$** | **PRESS** | **VIFmax** |
| Generic | 26.86***<br>(se 2.2)<br>(CI 22.4÷31.3) | | -0.005***<br>(se 0.001)<br>(CI -0.01÷-0.003) | | | | | -0.664 ***<br>(se 0.08)<br>(CI -0.83÷-.048) | | | | | 0.63 | 60.90 | 1.22 |
| | 25.56***<br>(se 2.23)<br>(CI 21.0÷30.1) | -0.008 ***<br>(se 0.001)<br>(-0.01÷-0.005) | | | -0.014 ***<br>(se 0.003)<br>(CI -0.02÷-0.009) | | | | | | | | 0.59 | 65.38 | 1.02 |
| | 24.11***<br>(se 2.14)<br>(CI 19.8÷28.4) | -0.007 ***<br>(se 0.001)<br>(-0.01÷-0.004) | | -0.003 ***<br>(se 0.001)<br>(CI -0.005÷-0.002) | | | | | | | | | 0.59 | 67.07 | 1.07 |
| Cabernet Sauvignon | 19.0***<br>(se 1.78)<br>(CI 15.1÷22.9) | -0.005 ***<br>(se 0.001)<br>(-0.01÷-0.003) | -0.0025***<br>(se 0.0004)<br>(CI -0.003÷-0.002) | | | | 0.007 ***<br>(se 0.001)<br>(CI 0.004÷0.01) | | | | | | 0.85 | 3.83 | 1.14 |
| | 19.2***<br>(se 1.62)<br>(CI 15.7÷22.7) | | -0.003 **<br>(se 0.001)<br>(CI -0.004÷-0.002) | | | | | -0.389 ***<br>(se 0.06)<br>(CI -0.53÷-0.25) | | | | | 0.77 | 5.18 | 1.20 |
| Chardonnay | 10.33***<br>(se 3.31)<br>(CI 3.1÷17.6) | | | | | | | -1.174 ***<br>(se 0.20)<br>(CI -1.61÷-0.71) | | -0.112 ***<br>(se 0.013)<br>(CI -0.14÷-0.08) | | 1.038**<br>(se 0.24)<br>(CI 0.49÷1.5) | 0.87 | 11.99 | 3.29 |
| | 16.11***<br>(se 3.33)<br>(CI 8.6÷23.2) | | | | | -0.030 ***<br>(se 0.004)<br>(CI -0.04÷-0.02) | | -0.935 ***<br>(se 0.19)<br>(CI -1.4÷-0.5) | | | 0.942**<br>(se 0.26)<br>(CI 0.37÷1.51) | | 0.82 | 16.22 | 2.35 |
| | 36.56***<br>(se 3.45)<br>(CI 28.8÷ 43.8) | | -0.007 ***<br>(se 0.001)<br>(CI -0.008÷-0.004) | | | | | -1.058 ***<br>(se 0.16)<br>(CI -1.4÷-0.7) | | | | | 0.81 | 18.11 | 1.22 |
| Shiraz | 17.61***<br>(se 1.898)<br>(CI 13.2÷22.3) | | | | | | | | -0.305 ***<br>(se 0.058)<br>(CI -0.45÷-0.17) | | | | 0.70 | 10.44 | |
| | 13.34***<br>(se 2.086)<br>(CI 9.8÷18.4) | | | -0.003 **<br>(se 0.001)<br>(CI -0.006÷-0.002) | | | 0.009 **<br>(se 0.003)<br>(CI 0.004÷0.014) | | | | | | 0.82 | 7.40 | 1.48 |

Significance; ** $p < 0.01$, *** $p < 0.001$, se=standard error, CI=95% confidence interval, PRESS = predicted residual sum of squares, VIFmax = maximum variance inflation factor, GDD_GS = growing season Growing degree days, DR_GS, DR_OF = growing season and October to February months diurnal ranges, DR_Jan, DR_Feb = January and February diurnal ranges, Rn_GS = growing season rainfall (mm), Tmn_RP , Tmx_RP = means of minimum and maximum temperatures during ripening period (°C), D25_GS = number of days with maximum temperature over 25°C during growing season, Rad_Oct, Rad_Nov = mean daily radiations in October and November (MJ/m$^2$)

## 3.4 Discussion

The aims of this study were to investigate the influences of climate (using a natural climate-gradient) on key berry quality attributes for three major winegrape varieties, and to develop empirical climate-based models that describe the observed responses. Weekly berry sampling along a 700 km transect, covering all the Western Australian wine growing regions, provided the relevant berry quality data and climate-gradient to address the aims. Such a long sampling transect is also likely to generate "gradients" in variables other than climate (e.g. soil type, management). Nonetheless, when the results were examined at a standardized berry maturity: 1) there were clear differences, particularly in berry anthocyanin concentrations, TA and to lesser extent in pH along the transect, and 2) more significantly, most of the variations in these berry quality attributes along the transect were accounted for using variations in the prevailing climates of the sites. As such, this provides a clear indication that (a) macroclimate exerts a dominant influence in shaping the regional pattern of berry quality (*sensu* (Winkler, 1974, Smart, 1985)), and (b) the information so gleaned can, with caution, be used for quantitative evaluation of impacts of climate change on berry quality. Details are discussed in the following sections.

### 3.4.1 Variations in berry quality attributes along the climate gradient

Development of berry quality attributes and their levels at maturity are influenced by several factors such as variety, climate and management practices (Jackson and Lombard, 1993, Guidoni et al., 2008). In this study, where possible, vines with similar clonal material and management were chosen (Table 3.1) to minimize confounding effects of non-climatic drivers on grape quality. The results have revealed that when maturity is standardized and confounding factors are partly controlled for, there are clear patterns in the levels of berry quality attributes along the climate gradient: levels of TA and anthocyanins from the warmer sites were lower than those from cooler sites when the sites were described by the average growing season temperature. These results are consistent with qualitative descriptions of the relations between berry quality and site temperature (Winkler, 1974, Lakso and Kliewer, 1975, Gladstones, 1992, Mullins et al., 1992), and indicate the influential role of temperature on berry quality (Buttrose et al., 1971). Levels of berry pH, on the other hand, showed no strong trend across sites when the sites were described by the long term temperature alone.

### 3.4.2 Anthocyanins and climate relationship

Accumulation of anthocyanins commences at véraison for red grape varieties (Mullins et al., 1992) and the accumulation process is influenced by environmental and management conditions (Kliewer and Weaver, 1971, Downey et al., 2006). It was, thus, anticipated that anthocyanin levels would show strong association with ripening period climate variables. This was generally borne out by the data showing that some of the strongest (negative) correlations were with climate variables from January and February (months which make up the ripening period). More generally, for both red varieties, higher berry anthocyanin concentrations were found in grapes from cooler rather than from warmer sites along the climate gradient. Such an inverse relationship between temperature and berry anthocyanin concentration is consistent with earlier reports (Kliewer and Torres, 1972, Kliewer, 1977, Mori et al., 2005).

For Cabernet Sauvignon, strong negative associations between anthocyanin concentrations at maturity and January average or maximum temperature, or duration of hours > 25 $^{o}$C or > 30 $^{o}$C during the ripening period were observed. Surprisingly, these results from the 700 km long climate gradient study are remarkably consistent with results of Mori et al. (2007) from a controlled environment study that demonstrated striking effects of high daytime temperature (35°C), which caused more than 50% reduction in Cabernet Sauvignon anthocyanin accumulation compared to control treatment (25°C day time temperature). Moreover, the associations between the length of time over 25°C or 30°C and anthocyanin concentration are in agreement with the results by Cahill (2009) who reported negative relationships between Pinot Noir anthocyanins concentrations at harvest and length of time over 22°C during post harvest period of previous season or length of time for 16°C to 22°C temperature range during flowering to véraison period, despite the different time frames used for this study and the reference study. Net anthocyanin accumulation obviously is a balance between synthesis and degradation; and according to Mori et al. (2007) low levels of anthocyanins, at least in Cabernet Sauvignon, under high temperature conditions result primarily from increased degradation and partly from reduced synthesis.

The pattern of Shiraz anthocyanin concentrations across sites was similar to that of Cabernet Sauvignon, maintaining the general trend of higher concentration of anthocyanins in grapes sampled at cooler sites. However, the average minimum temperature in January emerged as the most influential variable for Shiraz anthocyanin concentration at common maturity. As reviewed by Jackson and Lombard (1993), grape anthocyanins are reduced or enhanced above or below a night time temperature of 15°C, respectively. For the majority of the sites in this study, the average night time temperature was over 15°C in January and, therefore minimum temperature may have exerted more influence on Shiraz anthocyanin concentration than the other climate variables. In this regard, it is worth noting that climate projections indicate a relatively greater rise in the minimum temperature, during the ripening period.

The degree of association between grape anthocyanin concentration at maturity and the maximum temperatures in October and January were similar. As such, this is contrary to the expectation that anthocyanin accumulation is more influenced by the ripening period climate than by climatic events prevailing at the start of the growing season. Indeed, other climate indices for the month of October also showed consistently moderate to strong influence on (correlation with) berry quality attributes. One possible explanation is that warmer temperature early in the growing season shortens the growing season (Coombe, 1988) and thereby bringing forward the ripening to the warmer period, which is detrimental for anthocyanins accumulations in berries as discussed above. The strong inverse relationships between the maximum temperature in October and the dates of maturity for all three varieties (data not shown) support this contention. A further possibility is that warmer events early in the spring (while soil moisture is still high) favour increased vegetative growth which often tends to lessen anthocyanins concentrations (Smart et al., 1988).

Of all the bivariate correlations between the anthocyanin levels and climate variables, only those with the water-related variables (available soil water holding capacity, rainfall) had positive signs. And of these, only the correlations with rainfall in the September-November period were significant. While increased moisture avilability late in the growing season is often reported to reduce anthocyanin levels (Jackson and Lombard, 1993, Chalmers et al., 2010), it appears that improved water availability early in the growing season is beneficial as it promotes the initial and subsequent adequate vegetative growth (Keller et al., 2010) and, hence, proper development of the berry and its composition at later stages. In summary, for both red varieties, berry anthocyanin concentrations at the common maturity TSS significantly declined with increasing temperature along the sampling transect. This, implies a potentially adverse effect of warming climate on berry colouration and fruit quality.

### 3.4.3 Acidity and climate relationships

For all three varieties, bivariate correlation analyses of TA at maturity with climate have discerned at least three salient features: 1) TA is negatively correlated with almost all monthly climate indices throughout the growing season except rainfall, 2) by contrast, the TA correlations with rainfall variables are positive, and 3) the strength of the associations (regardless of its sign) between TA and climate variables steadily increases from early growing season towards the berry ripening period indicating that the ripening period climate is more influential in determining levels of berry quality components at maturity (de Orduna, 2010, Buttrose et al., 1971, Jackson and Lombard, 1993). In particular, across varieties, some of the strongest and most consistent negative associations of TA were with maximum temperatures. This may reflect the fact that, in grapes, tartaric and malic acids constitute most (up to 92%) of total titratable acidity (Kliewer, 1966) and that respiration of grape acids, particularly malic acid, increases with increasing temperatures (Coombe, 1987, Sweetman et al., 2009). As indicated above, only rainfall variables were found to have positive influence on TA levels at maturity. The precise mechanism how rainfall favours high TA levels is not clear, but possibilities include indirect influences via (a) lowering of air temperature with an increase in rainfall, and b) increased vegetative growth with increased moisture availability – both of which would favour TA levels.

### 3.4.4 pH and climate relationships

The associations between pH and monthly or ripening period temperature variables were generally positive. Dry (1983), using a broadly similar approach, also found a positive relationship between Shiraz berry pH and January average temperatures. Considerable increases in berry pH occur during berry ripening (Winkler, 1974). However, influences of ripening period temperatures on pH were relatively modest for the red varieties particularly in Cabernet Sauvignon.

Influences of moisture-related varaibles (rainfall, available soil water holding capacity) on berry pH levels, apart from being moderate, were also inconsistent among varieties. All sites applied different levels of supplementary irrigation during the later periods of the growing season and therefore may have contibuted to the lack of consistency of moisture-related variables on pH levels at maturity. According to Smart (1985), of the three berry quality attributes examined here, berry pH is the most sensitive to climate conditions within a vine canopy (microclimate). The within vine microclimate can vary considerably within a field as a function of vigour. It is, thus, probable that microclimate variations masked the macroclimate influence on pH, and hence “lack” of a strong pH trend along the climate gradient.

### 3.4.5 Temperature influence on rates of change of berry quality attributes

Anthocyanin concentrations for both red varieties were negatively related to (véraison period) temperature. However, unlike TA, anthocyanin concentration of Cabernet Sauvignon showed a wider range of variation across the temperature gradient than those of Shiraz. Consequently, the decline in anthocyanins with increasing temperature was higher for Cabernet than for Shiraz. This outcome suggests that the degree of plasticity of a trait in a given variety rather than a variety's maturity grouping determines rate of change in a trait in response to temperature. Collectively, these contrasting results provide evidence for the differential influence of temperature not only among varieties but also on different berry quality traits within a variety, and hence underscore a need for caution on extrapolating impact of climate warming on other berry quality attributes and varieties.

In all three varieties, berry TA levels at a common maturity declined as the growing season average maximum temperature increased; however, the rates of decline were variety-dependent. Similar responses have been indicated in other varieties as a function of growing degree days (Winkler, 1974). The magnitudes of rates are by definition a reflection of the degree of each variety's TA variation. Thus, Chardonnay which showed the widest range of TA levels at common maturity had the largest rate of drop (0.66 (g/L) per°C warming in the growing season average maximum temperature), followed by Shiraz (0.51 (g/L)); while Cabernet Sauvignon which had the narrowest range of variation, its TA dropped at half the rate of Chardonnay. These rates are inversely proportional to the varieties' maturity grouping (Gladstones, 1992) -i.e., the early and late maturing varieties had the largest and smallest rates of acid loss, respectively while an intermediate rate was observed for Shiraz from the medium maturity group. As such, at least for TA, these results are consistent with the view that the largest rate-difference occurs between early and late maturing varieties (Winkler, 1974). These results also suggest that, other factors being the same, increased warming will have a relatively greater negative impact on Chardonnay TA than of Shiraz or Cabernet Sauvignon.

### 3.4.6 Temperature influences on rates of change in anthocyanin concentrations and TA relative to sugar accumulation rates

The relative rates of change in the berry quality components during ripening have crucial importance for viticulture since the ultimate quality of wine depends on the balance between TSS and berry quality components at harvest. In practice, TSS is used to assess berry ripeness with a tacit perception that accumulation rates of other berry quality components are synchronous or closely coupled with soluble solids (but see Winkler, 1974; Gladstones, 1992). This study showed that for some combinations of variety and berry quality attributes (e.g., TA in Chardonnay and anthocyanin concentration in Cabernet Sauvignon) warmer ripening conditions significantly altered the rates of change of these attributes relative to soluble solids accumulation rates. Sadras et al. (2007b) also found decoupling of anthocyanin and sugar accumulation rates in Cabernet Sauvignon with increasing water stress during the ripening period although in this case anthocyanins were favoured: the relative accumulation rates shifted from nearly isometric in vines that received 50% more water than “standard” irrigation volume to increasingly allometric (in favour of anthocyanins) as irrigation volume declined to 40% of the “standard” level. These two lines of evidence show that heat and water stress elicit contrasting responses in anthocyanin accumulation rates relative to total soluble solids. In terms of the results observed from this study, the consequences of significant slowing of anthocyanin accumulation rates relative to the rates for soluble solids are manifest in reduced colouration of Cabernet Sauvignon berries under warmer ripening conditions (see Figure 3.3); but Shiraz appears relatively less sensitive. The decoupling of sugar and anthocyanin accumulation rates is understandably described in terms of the differential temperature optima of the respective processes (see Sadras et al., 2007b). The relative insensitivity of Shiraz suggests that, at least in this variety, the temperature optima ranges of processes responsible for sugar and anthocyanin accumulation are comparable. However, further evaluation whether this is the case is warranted.

### 3.4.7 Models for predicting responses of berry anthocyanins, TA and pH to changing climate

A largely north-south sampling transect – straddling all the Western Australian wine regions was set up that provided sizeable gradients of climate variables. These climate data in conjunction with grape quality data collected along the climate gradient enabled formulation of parsimonious models (Table 3.4, 3.5, and 3.6) that describe (can be used for evaluating) responses of some of the key berry quality attributes of major winegrape varieties to changing climatic conditions.

For each of the three berry quality attributes examined here, it was possible to describe a significant proportion of their variation across the climate gradients using generic or variety-specific models (Tables 3.4, 3.5, and 3.6). That it is possible to describe, albeit it to varying degrees, each berry quality attribute using a generic model suggests that regardless of variety, a given berry quality attribute is influenced by a common underlying process or if different processes are at play these respond similarly to the same set of climate variables. Nonetheless, the descriptive performances of the generic models, except of pH, were generally lower than the variety-specific models, even when the climate variables were identical in both models. This, however, is not unexpected considering the three varieties fall into three different maturity groups. That is, the critical berry development and/or ripening periods and the climate variables that prevail during the corresponding times are different for different varieties. For this reason, the discussion that follows generally focuses on the variety-specific models.

As described earlier, bivariate correlation analyses indicated moderate to strong associations of each berry quality attribute with many of the basic and derived climate variables. From the model building and selection processes, however, relatively few of the climate variables appeared important for describing berry quality responses (Table 3.4, 3.5, and 3.6). Such a high screening out is, in part, a reflection of the high degrees of interdependencies among the starting set of climate variables.

It is expected that climate components prevailing during development of a berry exerts more influence than other period. Consistent with this, models of anthocyanins were generally dominated by climate indices derived from part or whole of the anthocyanin accumulation period. The significant variables identified for describing anthocyanin concentration were temperature indices from the month of January and/or the ripening period, rainfall and radiation. The impacts of temperature variables (when present in the models alone or in combination with other climate variables) were negative, which is in accord with the widely understood effect of temperature on anthocyanins (see previous section). With respect to radiation, variable apparent effects were observed depending on whether it was considered alone (Figure 3.4) or together with temperature (Table 3.4). Reported effects of radiation on berry anthocyanins span the full spectrum of possible responses ranging from an increase (Kliewer, 1977, Smart et al., 1988, Keller et al., 1998, Bergqvist et al., 2001, Spayd et al., 2002), no effect (Downey et al., 2004, Cortell and Kennedy, 2006) to a reduction (e.g., Haselgrove et al., 2000) in anthocyanin concentrations as radiation levels increase. The diversity of reported responses is likely to reflect differences in experimental set up with variable control in temperature (Downey et al., 2004). However, even when temperature is carefully controlled for, variable though qualitatively similar, responses to radiation are reported: increase (Spayd et al., 2002) and no effect (Downey et al., 2004, Cortell and Kennedy, 2006). However, from multiple regression analyses (Table 3.4) it emerged that when radiation and temperature from the ripening period occurred together in anthocyanin models, the radiation term was positive while temperature was consistently negative. This approach appears to be useful in differentiating the effects of temperature and radiation on berry anthocyanins levels, and supports the suggestion that the apparent negative effect of radiation is a reflection of high temperature load effect (Haselgrove et al., 2000, Bergqvist et al., 2001, Downey et al., 2004).

pH was the most recalcitrant of the berry quality attributes to describe adequately in terms of macroclimate variations along the climate gradient. Only about half the variations in pH could be described by a generic model containing growing degree days during growing season and October vapour pressure deficit. The influences of both variables on pH were positive (same as in the bivariate analyses). Boulton (1980) has shown that berry pH is primarily a function of the levels of organic acids and the monovalent cations, mainly potassium and partly sodium. It can thus be argued that to the extent climate influences pH, the effect is indirect via the levels of acids and cation uptake. In this respect, the positive influence of high growing degree days is likely to relate to its negative impact on acidity (e.g., Winkler et al., 1974; this study) which, other things being equal, elevates berry pH. On the other hand, how vapour pressure deficit in October positively influences berry pH is less clear. However, high vapour pressure deficit early in the growing season (October) when soil moisture is relatively adequate promotes water and potassium uptake (Rankine et al., 1971, Ruhl, 1992) and sequestration in the vine system. Part of the potassium so sequestered is remobilized during ripening to augment the potassium levels in berries (Conradie, 1981), which may then contribute positively to berry pH (Rankine et al., 1971, Boulton, 1980).

Across all three varieties, high proportions of the TA variations along the climate gradient were accounted for. The most pertinent variables for describing TA variations along the climate gradient were primarily temperature and temperature derived variables, and growing season rainfall. The joint influences of these temperature and rainfall variables on TA were directionally the same as the individual variable effects (i.e., the bivariate correlations). Although the negative effect of maximum temperature on TA is well acknowledged, an outstanding observation from this gradient study is the prevalence of the ripening period minimum temperature in the TA models of all three varieties. Further, the impact of this variable on TA was without exception negative. Given that the minimum temperatures appear to show relatively fast increase under climate change, increased acid loss may occur even without an increase in the maximum temperature.

Although the models presented here accounted for high proportions of the variation in the grape quality attributes examined for all three varieties, caution is needed to apply these models in other environments. As with any other regression models, these empirical models are not free of shortcomings since these were not based on mechanistic processes although known effects on the (direction of) impact of specific climate variables on berry quality were taken into account in the model selection process. Further, non-climatic factors (such as crop load, canopy manipulation, soil management, etc.) which can influence berry quality attributes (e.g., Kliewer and Weaver, 1971; Smart et al., 1985; Jackson and Lombard, 1993) were not explicitly incorporated. Additionally, in this study, climate variables whose values are functions of time, for example growing degree days were used. On the other hand, levels of the berry quality attributes are also time dependent. Hence it is possible that regression between such time-dependent variables yield fortuitous association (Jones and Davis, 2000a). However, the grape quality attributes examined for this study were not elapsed time dependent since these were standardized to a common maturity TSS (22 °Brix) across sites. Therefore, it is argued that even though some time-dependent variables are included in the models, the results are unlikely to be coincidental, and the inferences drawn from the models are valid.

### 3.5 Conclusion

This study has demonstrated that for all three major winegrape varieties examined there were strong trends particularly in berry anthocyanin concentrations and titratable acidity along the 700 km transect (climate gradient). This demonstrates that despite variations in a range of factors that can potentially affect berry quality, climate exerts a dominant role in shaping the regional pattern of berry quality. This validates the use of natural-gradients of climate as a surrogate for evaluating potential impacts of changing climate on some aspects of viticulture. These observations were used to develop empirical models that, with consideration of the caveats discussed above and further validation, could facilitate quantitative climate change impact analyses for these berry attributes.

# CHAPTER 4. PROJECTED PLIMATE CHANGE FOR THE WESTERN AUSTRALIAN WINE GROWING REGIONS: ANALYSIS WITH FINE SPATIAL RESOLUTION CLIMATE INDICES

## 4.1 Introduction

### 4.1.1 Climate in Western Australian wine regions

Wine growing regions of Western Australia (WA) are mainly located in the southwest corner of the state (Figure 4.1). Climate conditions for WA viticultural regions have been well studied and documented in the past in relation to different grape varieties and wine styles (Jackson and Spurling, 1988, Gladstones, 1992, Hall and Jones, 2010). The Mediterranean climate of the southwest of WA provides the environmental conditions conducive for winegrape growing making the wine industry an important player in the national and international market of premium wine production (DAFWA, 2006) .The growing season temperature is about 21°C in the northern Swan District, but the majority of the regions and sub-regions in the southern districts have a GST of between 17 to 18°C (Gladstones, 1992). Majority of the regions receive most of their rainfall during winter, requiring supplementary irrigation in summer during the grape growing season through harvesting water from surface catchment.

Areas of southwest of WA covering the cool climate wine growing regions in WA, known for producing premium wine, are projected to receive 2 to 20 percent less winter rainfall (Bates et al., 2008) and become 0.5 to 2.1°C warmer during summer by 2030, and the magnitude of these changes is projected to increase later in the century (Whetton et al., 2005b, Bates et al., 2008). Furthermore, increasingly dry conditions, an increased number of hot days with a maximum temperature exceeding 35°C, and elevated evaporation rates are likely to occur in the southwest of WA in coming decades (Hope, 2006, CSIRO and BOM, 2007). However, the full impacts of these changes on Western Australian wine growing regions are unknown.

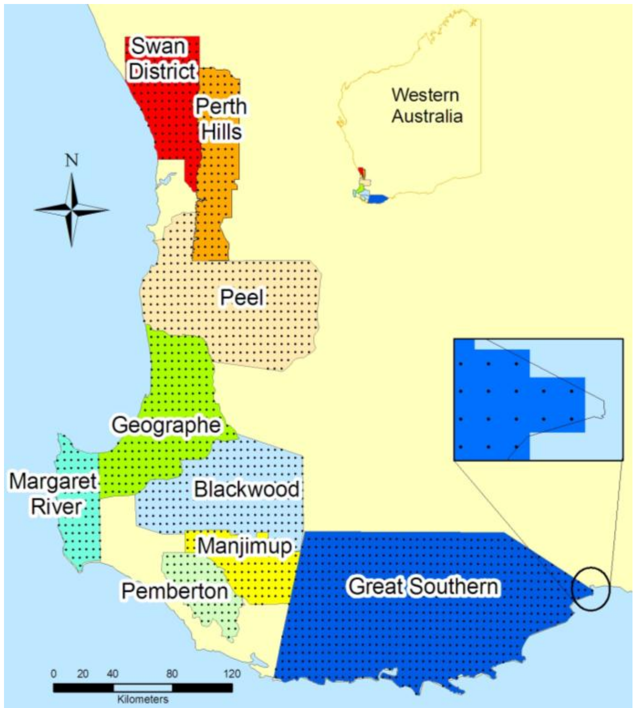


Figure 4.1 Geographic Indications of Western Australian wine regions. Geographical locations are indicated on the inserted Western Australian map (top inset). Statistics of climate surfacesfor a wine regionv were calculated from pixels whose centroid were laid within a region boundary line as illustrated in bottom right inset. Pixel size is ~5 km

Only a limited number of impacts studies in viticulture have been undertaken for Australian conditions. For example, Webb (2006) is the first comprehensive study to examine climate change impacts on temperature and rainfall derived from the CSIRO Mk3.0 and HADCM3, global climate models (GCMs), and a limited area model (DARLAM) for 2030 and 2050 periods. Hall and Jones (2009) examined temperature based climate indices such as mean temperature during October to April, ripening period temperature, and accumulated Biologically Effective Degree Days (BEDD) for Australian wine regions using the CSIRO Mk3.0 for 2030, 2050 and 2070 periods. According to their results, the Perth Hills and Kangaroo Island wine regions will experience the highest (up to 2.7°C by 2070) and lowest warming (1.3°C by 2070) in October to April mean temperature compared to current (1971 to 2000) climate.

### 4.1.2 Uncertainties in climate change projections

Uncertainties surrounding future greenhouse gas emission scenarios, that depends on interactions between future social and economic development, as well as climate system responses to the increased atmospheric greenhouse level, limit the predictability of future climate change. There are many sources of uncertainty inherent in the modelling and prediction of climate change. As summarised in the IPCC report (IPCC, 2007) the major sources of uncertainty include:

1. Architectural and parameters differences in GCMs. GCMs share the same general form, consisting of a large system of differential equations designed to simulate long-term changes in atmospheric and ocean systems. However, there are a large number of choices of functional form for equations, specification of variables, and the details of the process and estimation and the different choises lead to different results. Parameters of any GCM are estimated with reference to the available data. Given a finite data set, parameters are inevitably estimated with error, and this error creates uncertainty with respect to predictions. The crucial parameter in a GCM is climate sensitivity, that is, the sensitivity of equilibrium global temperature to a given change in "forcing".
2. Uncertainty about Emissions. Perhaps the most important single source of uncertainty, in forecasting likely climatic conditions in the future, relates to future growth of, or reductions in, emissions in greenhouse gases. The relationship between climate change and uncertainty about emissions is complicated by the fact that the policy choices that will help to determine future growth in emissions are themselves a response to projections of future climate change.
3. Uncertainty about Other Forcings. Although the growth in emissions of greenhouse gases is the main cause of the climate change, many other forcings affect climate. None of these forcings demonstrate a consistent long term trend, and therefore none can explain the long term growth in mean global temperatures, but uncertainty about these forcings contributes to uncertainty about future warming. For example, the variation in the intensity

of solar output and changes in the concentration of various aerosols including black soot.

4. Feedbacks, Sinks and Lags. GCMs take account of feedbacks and lags operating within the atmosphere and, to some extent, the capacity of oceans and other global systems to absorb $CO_2$. But there are many other potential feedbacks that are poorly understood. For example, higher temperatures may lead to more, and more severe, bushfires, with a resulting increase in $CO_2$ emissions.

Consequently, GCM project future climate differently depending on what climate and emissions scenarios they take into account. For example, by 2030, the potential warming range in Australia is projected to be between 0.6 and 1.5°C with a climate system uncertainty for an A1B emission scenario, but this range increases to 0.4 to 1.8°C when multiple emission scenario uncertainties are considered (CSIRO and BOM, 2007). Moreover, the uncertainty range increases with the increases in projection time such that ranges in the uncertainty for 2070 is larger than that of 2030 (CSIRO and BOM, 2007).

### 4.1.3 Scale issues with global climate model outputs for impacts assessment

Global climate modles (GCMs) outputs have a spatial resolution of the order of about 200 to 400 kilometres. Thus, it can be advantageous that GCM outputs are downscaled to a suitably fine spatial resolution for local or regional climate change impact analysis (e.g. Easterling et al. (2001)). Dynamical downscaling involves using a regional climate model nested in a GCM and requires large computational resources. Statistical downscaling relies on adequate historical observation for the climate variable of interest at the local scale (Benestad, 2004). Several statistical downscaling approaches, for instance, stochastic downscaling (Bates et al., 1998, Charles et al., 1999) or pattern scaling (Suppiah et al., 2007, Mpelasoka et al., 2008) have been successfully used in Australia for regional climate change projections in various impacts studies. We used pattern scaling approach to construct finer scale climate data from coarse scale GCMs outputs.

The objective of this chapter is to quantitatively assess the impacts of climate change on a range of climatic indices in WA wine regions. The main differences between this study and previous studies are: 1) the broader range of climate indices examined including temperature, rainfall, frequency of extreme hot days, and radiation; 2) the regional focus of the research using fine resolution downscaled (~5 km) climate projections.

## 4.2 Materials and Methods

### 4.2.1 Study areas

A requirement of the Geographical Indications (GI) regulations is that Australian wine regions must each have their own distinct measurable differences from adjoining regions as well as a measurable homogeneity over its area for grape growing (Wine Australia, 2011). Thus, it is important to assess the potential changes in the existing characteristics of the wine regions brought about by climate change. For this reason, a series of polygon features of WA wine regions in Geographic Information Systems (GIS) were created by digitising the wine region maps (Figure 4.1) in compliance with the regulations, and used them for extracting and calculating climate index statistics for the individual regions.

### 4.2.2 Climate model selection

The use of a single projection for future climate may be sufficient to illustrate the type of changes or test a particular method of downscaling, but for other purposes it is recommended to use multiple projections to address the uncertainty range (CSIRO and BOM, 2007). For this study, 10 GCMs (Table 4.1) that were included in the Fourth assessment report of the Intergovernmental Panel on Climate Change to address the climate change uncertainty from climate models. These models were selected on the basis of their performances evaluated by Perkins et al., (2007), and CSIRO and BOM (2007) for their ability to reproduce current climate for Australian conditions.

Perkins et al. (2007) used probability density functions to evaluate how well a climate model reproduces the observed data. By this approach, a score of 1 is given to a model if the reproduced and observed climate variables have perfectly matching distributions. If the distributions between the observed and modelled climate variable do not match, then the model performance score will be 0, indicating poor prediction. Selected GCMs and their scores are presented in Table 4.1. Minimum temperature, maximum temperature, and rainfall selections (columns 3 to 5) were based on the above approach for the climate variables specifically in the southwest of WA.

The CSIRO and BOM (2007) scores are based on similarities between observed and simulated climate variable maps. They give a score of 0 to a non-match and 1 to a model that perfectly matches the observed climate variable. Scores shown in Table 4.1 (column 5) are averages of the individual scores of temperature, precipitation, and pressures across four seasons.

Table 4.1 Global climate models used and their performance scores for reproducing past climate

| | Climate models | †Scores by §Perkins et al 2007 | | | †Scores by CSIRO 2007 | Model developers & originating country |
|---|---|---|---|---|---|---|
| | | Tmin | Tmax | Rainfall | | |
| 1 | CCCMA-CGCM3.1 | ~0.86 | ~0.87 | ~0.60 | 0.52 | Canadian Centre for Climate Modelling and Analysis, Canada |
| 2 | CSIRO Mk3.0 | ~0.87 | ~0.81 | ~0.70 | 0.60 | CSIRO, Australia |
| 3 | CSIRO Mk3.5 | - | - | - | 0.61 | CSIRO, Australia |
| 4 | IPSL cm4 | ~0.89 | ~0.94 | ~0.62 | 0.50 | Institute Pierre-Simon Laplace, France |
| 5 | MIUB Echo G | ~0.67 | ~0.88 | ~0.82 | 0.63 | Meteorological Institute of the University of Bonn Germany |
| 6 | MRI CGCM2.3.2A | ~0.87 | ~0.82 | ~0.61 | 0.60 | Japan Meteorological Agency, Japan |
| 7 | MPI Echam 5.0 | ~0.86 | - | ~0.83 | 0.70 | Max-Planck-Institute for Meteorology, Germany |
| 8 | MEDRES Miroc 3.2 | ~0.88 | ~0.90 | ~0.80 | 0.61 | Centre for Climate System Research, Japan |
| 9 | GFDL-CM2.1 | ~0.87 | - | ~0.75 | 0.67 | Geophysical Fluid Dynamics Laboratory, USA |
| 10 | GFDL-CM2.0 | - | - | ~0.79 | 0.67 | Geophysical Fluid Dynamics Laboratory, USA |

†Methods of model performance score calculations are different. See text for more descriptions. §Scores presented in this table are based on evaluations of the models to reproduce past climate in southwest of Western Australia. Blank cells indicate that particular climate variable was not evaluated by above studies. Original spatial resolutions of these models ranged between 175 to 400 km, but for this study they were downscaled to ~5 km. Climate model scores are obtained from works by Perkins et al. (2007) and SCIRO (2007).

4.2.3 Construction of downscaled climate projections

Regional projections of future climate sequences were constructed with the following steps:

1. Three sets of climate change projections associated with low, medium and high global average warming estimates associated with the Intergovernmental Panel for Climate Change (IPCC) Special Report on Emissions Scenario (SRES) A2 were accessed from the Program for Climate Model Diagnosis and Intercomparison (PCMDI) database for 2030, 2050 and 2070 periods. For the 2030 period, the projected low, medium and high warming in global mean temperature relative to 1990 are 0.48°C, 0.80°C and 1.28°C, respectively. Similarly increase of 0.84°C ,1.4°C and 2.24°C for 2050 and 1.35°C, 2.25°C and 3.6°C for 2070. These estimates of increases in mean global temperature are inferred from the IPCC Fourth Assessment Report (Meehl et al., 2007) and the latest climate change projections for Australia (CSIRO and BOM, 2007). They take into account the uncertainties (under the A2 emission scenario in this case) associated with greenhouse gas emissions, global climate sensitivity to greenhouse gases and the amplification of climate change due to carbon cycle feedbacks. The A2 emission scenario story line exemplifies a differentiated world with independently operating nations with continuously increasing population, and uneven technological and economic growth among the regions in the future (Houghton et al., 2001). The A2 scenario is at the higher end of the SRES emissions scenarios after A1FI as shown in Figure 4.2. Due to the constraints of resources and time this study opted for the A2 scenario. From an impacts and adaptation point of view, if one can adapt to a larger climate change, then the smaller climate changes of the lower end scenarios can also be adapted to (NARCCAP, 2011).

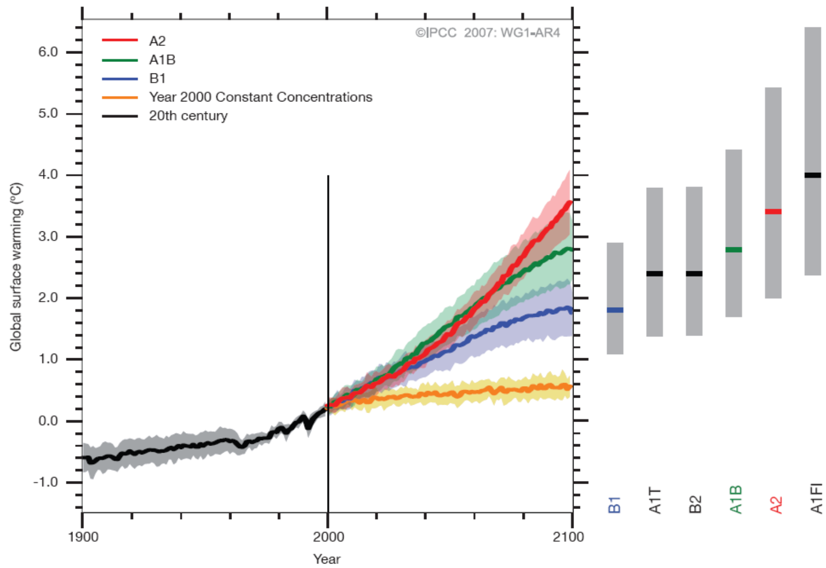


Figure 4.2. Global average warming relative to 1980 to 1990 average for the scenarios A2, A1B and B1. Shading denotes the plus/minus one standard deviation range of individual model annual averages. The orange line is for the experiment where greenhouse gas concentrations were held constant at year 2000 values. The grey bars (right) indicate the multi-model mean warming (solid line within each bar) and the likely range of warming by the 2100 for the six SRES marker scenarios. (IPCC 2007)

2. Local patterns of change in climatic variables for each GCM grid-cell were calculated on a seasonal basis (December-January-February, March-April-May, June-July-August and September-October-November). Due to gradually increasing greenhouse gas emissions, GCMs produce a gradually increasing temperature over time, the magnitude of which is influenced largely by the climate sensitivity of the GCM and the emission scenario. Changes in local (grid-cell) climate variables including rainfall, temperature, relative humidity and radiation generally show a linear relationship with climate change, even though the rate of climate change is non-linear. Due to this linear relationship, patterns of change were calculated by regressing each local climate variable on an annual basis for each GCM grid-cell, against global temperature. The regression process standardizes the climatic variable response as a function of average climate warming, and also removes most of the errors associated with the simulation of historical climate as the change relative to current climate is estimated, rather than the climate simulation itself (Hennessy et al., 1998 ). The major advantages of this approach are that: (1) the entire period of simulation contributes to the

construction of climate change patterns; (2) errors in the simulation of local climate are not a part of the analysis; and (3) transitory and non-linear influences such as decadal-scale variability are removed from the climate change signal. The projections for each variable were then produced by scaling local patterns of change by the projected low, medium and high warming ranges for the three periods. For example, a high climate warming of 2.24°C in 2050 is multiplied by the patterns of change of each climate variable to produce projections for that period.

3. The projections were subsequently applied to the observed historical daily time series (1975-2005) on a 5km grid to generate plausible future climate sequences for each grid-cell, as inputs for climate change impact studies at a 5km resolution. The gridded historical time series climate data was obtained from the Australian Water Availability Program. Scenarios of future sequences of daily minimum and maximum near-surface air temperatures, rainfall, incoming radiation, and atmospheric vapour pressure were constructed for this study.

This approach has been widely used for climate change impact modelling (Whetton et al., 2005b, Zhang, 2005, Mpelasoka and Chiew, 2009). However, the continuation of the pattern of variability by simply perturbing the present climate sequences into the future may understate the range of possible future climate variability. Nevertheless, this approach is simple to use, and it considers relative change in monthly or seasonal climate data and therefore can be used with the more readily available GCM simulations for different ensemble runs and different emissions scenarios. Different ensemble runs and emissions scenarios are useful to take into account the large uncertainties associated with climate change scenarios and the GCMs' simulations of local climate.

Climate change uncertainties associated with future emissions of greenhouse gas, and climate sensitivity to the increasing greenhouse are addressed by using low, medium, and high representative warming ranges under the A2 emission scenario for this study. This resulted in 30 different possible climate projections (3 warming ranges x 10 model outputs), per time period, introducing a range of uncertainties. For this study, after determining median growing season temperature (GST) projections across the wine regions, the number of models was reduced from ten to two, which represent the highest (high warming hereafter) and the lowest warming (low warming hereafter) in the median GST across regions. The high and low warming ranges capture the broadest uncertainty ranges among the GCM used. However, an estimation of the possible warming range during the grape growing season by the models might help stakeholders devise a more resilient strategy to deal with the potential changes in future climate.

### 4.2.4 Viticultural climate indices

The effect of climate on winegrape is well studied and a number of climate indices have been developed to assess and characterise the conditions of potential and existing wine regions for their suitability for growing certain grape varieties as well as implementing particular management practices appropriate to the different conditions. However, it is acknowledged that there is no single index that describes a climate system that influences plant growth in a complex way. For this study, several climate conditions were examined under current and future climates for the regions of interest. Respective indices and their basic statistics were derived from long term (31 years) climate data centred at the year 1990 as current, and the years 2030, 2050, and 2070 as future climate conditions.

#### 4.2.4.1 Temperature during grape growing and non-growing season

The period between the beginning of October and the end of April is usually considered the standard winegrape growing season in the Southern Hemisphere. Temperature during this period is one of the primary climate variables defining the heat requirements of vine growth and has been used as a criterion of a region's potential to grow particular varieties for premium winegrape production (Jones, 2006, Hall and Jones, 2009). Nevertheless, temperature during the winter dormancy season is equally important for grape production. Lower temperatures beyond that which a particular grape variety will tolerate could kill vines and put the industry at risk (Becker, 1985). This type of risk is not applicable for the regions in this present study. However, if the winter temperature gets too warm, especially under warming climatic conditions, it will lead to another concern for the grape growing industry as the timing of bud break is heavily dependent on chill accumulation during dormancy. This study used average temperatures during the periods, October to April and May to September as an index of climatic conditions during grape growth and dormancy. Average temperatures were calculated from daily mean temperatures for the above periods.

#### 4.2.4.2 Mean January temperature

Mean January Temperature (MJT) is another simple, but widely used temperature index for grape ripening capacity and berry quality in Australia (Smart and Dry, 1980, Webb et al., 2008b). Results of grape quality modelling discussed in Chapter 3 also demonstrated that MJT was the most influential climate variable for Cabernet Sauvignon and Shiraz anthocyanin levels at a berry TSS of 22°Brix. Mean January Temperature is calculated as an average of mean daily temperatures in January.

#### 4.2.4.3 Average temperature and its variability during grape maturity

Winegrape berry development and composition is greatly influenced by temperature and its daily fluctuation during ripening. For example, night temperature below or above 15°C during véraison is a critical factor determining the levels of berry acidity, colour, and flavour (Jackson and Lombard, 1993). Furthermore, Gladstones (1992) argued that the narrower the range of variation for a given average temperature during ripening, the better the quality of fruit at a given maturity level. The timing and length of the véraison period varies among varieties and regions depending on regional differences in climate. For simplicity, this study used February to March as the grape maturity period for the wine regions of interest. Average temperature and the summation of diurnal range during this period were used as indicators of temperature and its variability for the study regions. Average temperature is calculated from the mean daily temperature between 1st of February and 30th of March. The diurnal range is calculated as the difference between the daily maximum and minimum temperature, for the period of interest.

#### 4.2.4.4 Growing degree days

Growing Degree Day (GDD) is a commonly used indicator of the heat requirement for plant growth. It relies on the notion that active growth of a plant occurs when average temperature exceeds a threshold value. The threshold value varies among different plants, but 10°C is often taken as the threshold value for winegrapes, under which there is no active growth (Winkler, 1974). Daily GDD is calculated with following formula:

$$GDD = T_{av} - 10$$

where $T_{av}$ is the daily mean temperature as averaged from daily maximum and daily minimum temperatures. If $T_{av}$ is ≤10, then GDD = 0.

Another widely used heat accumulation index for viticulture is the Huglin Index which, although similar to GDD, gives more weight to maximum temperature and takes day-length into consideration. However, previous researchers have shown that these two indices are strongly related ($r > 0.95$) to each other (Hall and Jones, 2010, Jones et al., 2010). Thus, for this study the GDD index was investigated as the main heat accumulation indicator of grape growth. The GDDs were obtained by summing daily GDDs between 1st of October and 30th of April.

#### 4.2.4.5 Biologically effective degree days

The Biologically Effective Degree Day (BEDD) is based on the same GDD concept, but with additional adjustments: length of day, daily temperature variations, and most importantly the upper cut-off limit at 19°C. Gladstones (1992) used 40° latitude as a neutral point and argued that higher latitudes will get more heat accumulation due to longer day length and *vice versa* for lower latitudes. Another adjustment Gladstones (1992) introduced was based on the claim that a higher diurnal range will retard grape growth in spring due to its lower minimum temperature. However, it is acknowledged that this adjustment is eventually cancelled out under warmer conditions due to the upper cut-off limit adjustment in average temperature (Gladstones, 1992). Preliminary calculations in this study indicated that the maximum adjustments of an entire growing season BEDD at latitudes between 35° to 30° will be only 3.1 to 1.7% less compared with the unadjusted degree days at the neutral point. The wine growing regions in this present study lie between 31$^{o}$ to 35$^{o}$ latitude, thus suggests that the BEDD adjustments less than 3.1%. Moreover, the above adjustments are subjected to the upper cut-off limit adjustment, which strictly limits heat accumulations over 19°C average temperature, thus limiting the maximum daily heat accumulations to 9 units regardless of the adjustments, and the magnitude of the average temperature. Therefore, for this study we omitted the latitude and daily temperature range adjustments for daily BEDD calculations.

$$\textit{Daily BEDD} = T_{av} - 10$$

*(If $T_{av}$ is ≥19°C, then $T_{av}$ = 19°C. If $T_{av}$ ≤10°C , then the BEDD = 0)*

In this study the growing season BEDD is taken as the sum of daily BEDD between 1$^{st}$ of October and 30$^{th}$ of April.

Any increases in average temperature do not affect the BEDD if the average is above 19°C due to its upper limit. However, if heat accumulation is a limiting factor for optimal winegrape maturity, as it is in cooler growing regions, then the projected warming in climate might have a favourable impact on the region’s heat accumulation conditions. Therefore, for this study BEDD is included.

#### 4.2.4.6 Frequency of extreme temperature

Temperature outside the optimal range inhibits the enzymatic activity within grapes resulting in poorer colouration of berries and unbalanced sugar and acid concentrations for quality wine making. The exact optimum for flavour and aroma development is not known, but it is thought to be between 20 and

22°C. Beyond 25°C is considered ineffective for grape growth and balanced levels of fruit quality parameters (Kliewer and Torres, 1972, Gladstones, 1992). It is likely that the warmer temperature in future will increase the chances of increased heat stress for winegrapes. The frequency of days with maximum temperature over 25°C and 30°C were used in this study as additional indicators of extreme warm conditions for the grape growing season.

#### 4.2.4.7 Rainfall and its seasonal distribution

Sufficient rainfall and its seasonal distribution are crucial conditions for successful agriculture, especially if the rainfall is the primary source of water supply. In that case, rainfall and winegrape growth are inextricably related. Moisture stress during flowering and berry setting has a marked effect on yield, however, too much moisture during these periods may have negative effects. These might include reduced pollination, lack of sunshine and thus reduced photosynthesis, or overly vigorous growth that affects fruit setting and fruitful bud differentiation (Gladstones, 1992). A decline in future rainfall has important implications for WA wine regions that rely primarily on winter rainfall for adequate moisture availability in the beginning of the season and then stored water for supplementary irrigation later in the season when natural rainfall is inadequate. This study examined total rainfall for the whole grape growing season as an indicator of moisture conditions during vine growth, as well as winter, spring, summer, and autumn seasons as an assessment of seasonal distribution of rainfall in the regions of interest.

#### 4.2.4.8 Solar radiation

Radiation is one of the fundamental environmental factors for plant growth and has a dual effect on winegrapes: it affects vegetative growth through photosynthesis and thus contributes to the potential sugar levels in fruits during ripening (Kliewer and Antcliff, 1970), and during fruit maturity it also affects grape berry composition (Spayd et al., 2002, Bergqvist et al., 2001). As noted by Gladstones (1992), radiation during the spring, and just before and during véraison, is more important for winegrape growth than radiation during other periods. For this study we examined the sum of daily insolations ($MJ/m^2$) during the periods October to November, December to February, March to June, and July to September under current and projected climate conditions.

#### 4.2.4.9 Spatial and temporal scale of assessment

Statistics (minimum, lower quartile, median, upper quartile and maximum) of climate indices for the wine regions were calculated from pixels whose centre was located within the wine regions boundaries (Figure 4.1). Current and projected climate indices for the wine regions were reclassified with identical intervals to investigate spatial and temporal changes to the climate indices under climate change. An ArcGIS9.3 package (ESRI, Redlands, CA) was used for the spatial analysis.

In order to be consistent with previous studies (Hall and Jones, 2009, Webb et al., 2007, Webb et al., 2008a), and to provide long term insights on the potential impact of climate change on the WA wine industry, it was decided to focus on the years 2030, 2050, and 2070 as time frames for future climate assessment.

## 4.3 Results

### 4.3.1 Projected growing season temperature in the study regions

Among the 10 GCMs that were examined, the CSIRO Mk3.5 model projected high warming in the median GST across all wine regions (Table 4.2). On the other hand, averaged across the regions, the MEDRES Miroc3.2, MUIB ECHO.G and MPI-Echam5.0 models projected the low warming across the regions. Therefore it was decided to select the CSIRO Mk3.5 projections with high warming representative range, and the MEDRES Miroc3.2 model projections with the low warming representative range as representatives of high and low warming scenarios across the study regions.

Table 4.2 Median October to April temperature by 2030, 2050, and 2070 relative to 1990 base climate under A2 SRES emission scenario

| Time frame | Global Climate Models | With low range climate change (°C) Wine regions[†] | | | | | | | | | With medium range climate change (°C) | | | | | | | | | With high range climate change (°C) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | SD | PH | PL | GR | MR | BW | MJ | PM | GS | SD | PH | PL | GR | MR | BW | MJ | PM | GS | SD | PH | PL | GR | MR | BW | MJ | PM | GS |
| 2030 | 1. CSIRO MK3.5 | 0.7 | 0.7 | 0.7 | 0.6 | 0.5 | 0.6 | 0.7 | 0.6 | 0.6 | 1.1 | 1.1 | 1.1 | 1.0 | 0.8 | 0.9 | 1.0 | 0.9 | 1.0 | 1.7 | 1.7 | 1.6 | 1.5 | 1.1 | 1.4 | 1.4 | 1.3 | 1.3 |
| | 2. MRI CGCM2.3.2A | 0.7 | 0.6 | 0.6 | 0.6 | 0.5 | 0.6 | 0.5 | 0.5 | 0.5 | 1.0 | 1.0 | 1.0 | 0.9 | 0.7 | 0.9 | 0.8 | 0.8 | 0.8 | 1.6 | 1.6 | 1.5 | 1.4 | 1.1 | 1.3 | 1.3 | 1.3 | 1.2 |
| | 3. CSIRO MK3.0 | 0.7 | 0.6 | 0.6 | 0.6 | 0.5 | 0.6 | 0.5 | 0.5 | 0.5 | 1.0 | 1.0 | 1.0 | 0.9 | 0.7 | 0.9 | 0.8 | 0.8 | 0.8 | 1.6 | 1.6 | 1.5 | 1.4 | 1.1 | 1.3 | 1.3 | 1.3 | 1.2 |
| | 4. GFDL CM2.1 | 0.7 | 0.6 | 0.6 | 0.6 | 0.5 | 0.6 | 0.5 | 0.5 | 0.5 | 1.0 | 1.0 | 1.0 | 0.9 | 0.7 | 0.9 | 0.8 | 0.8 | 0.8 | 1.6 | 1.6 | 1.5 | 1.4 | 1.1 | 1.3 | 1.3 | 1.3 | 1.2 |
| | 5. CCCMA CGCM3.1 | 0.5 | 0.6 | 0.6 | 0.5 | 0.4 | 0.5 | 0.5 | 0.5 | 0.5 | 0.7 | 0.7 | 0.7 | 0.7 | 0.6 | 0.6 | 0.6 | 0.6 | 0.6 | 1.1 | 1.1 | 1.2 | 1.1 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| | 6. IPSL CM4 | 0.6 | 0.5 | 0.6 | 0.5 | 0.4 | 0.5 | 0.5 | 0.4 | 0.5 | 0.8 | 0.8 | 0.8 | 0.7 | 0.6 | 0.7 | 0.7 | 0.7 | 0.7 | 1.1 | 1.1 | 1.2 | 1.1 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| | 7. GFDL CM2.0 | 0.5 | 0.5 | 0.5 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.7 | 0.8 | 0.8 | 0.7 | 0.6 | 0.7 | 0.7 | 0.6 | 0.7 | 1.1 | 1.1 | 1.2 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| | 8. MEDRES MIROC3.2 | 0.5 | 0.5 | 0.5 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.7 | 0.8 | 0.8 | 0.7 | 0.6 | 0.7 | 0.7 | 0.6 | 0.7 | 1.1 | 1.1 | 1.2 | 1.1 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| | 9. MIUB ECHO.G | 0.5 | 0.5 | 0.5 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.7 | 0.8 | 0.8 | 0.7 | 0.6 | 0.7 | 0.7 | 0.6 | 0.7 | 1.1 | 1.1 | 1.2 | 1.1 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| | 10. MPI ECHAM5 | 0.5 | 0.5 | 0.6 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.8 | 0.8 | 0.8 | 0.7 | 0.6 | 0.6 | 0.6 | 0.6 | 0.7 | 1.2 | 1.2 | 1.2 | 1.0 | 0.9 | 1.0 | 1.0 | 0.9 | 1.0 |
| 2050 | 1. CSIRO MK3.5 | 1.4 | 1.3 | 1.3 | 1.2 | 0.9 | 1.1 | 1.1 | 1.1 | 1.1 | 2.3 | 2.2 | 2.1 | 2.0 | 1.4 | 1.8 | 1.8 | 1.8 | 1.8 | 3.2 | 3.0 | 3.0 | 2.8 | 2.0 | 2.5 | 2.5 | 2.5 | 2.5 |
| | 2. MRI CGCM2.3.2A | 1.3 | 1.2 | 1.2 | 1.1 | 0.9 | 1.1 | 1.0 | 1.0 | 1.0 | 2.1 | 2.0 | 2.0 | 1.9 | 1.4 | 1.7 | 1.7 | 1.7 | 1.6 | 3.0 | 2.8 | 2.8 | 2.6 | 2.0 | 2.4 | 2.4 | 2.4 | 2.3 |
| | 3. CSIRO MK3.0 | 1.3 | 1.2 | 1.2 | 1.1 | 0.9 | 1.1 | 1.0 | 1.0 | 1.0 | 2.1 | 2.0 | 2.0 | 1.9 | 1.4 | 1.7 | 1.7 | 1.7 | 1.6 | 3.0 | 2.8 | 2.8 | 2.6 | 2.0 | 2.4 | 2.4 | 2.4 | 2.3 |
| | 4. GFDL CM2.1 | 1.3 | 1.2 | 1.2 | 1.1 | 0.9 | 1.1 | 1.0 | 1.0 | 1.0 | 2.1 | 2.0 | 2.0 | 1.9 | 1.4 | 1.7 | 1.7 | 1.7 | 1.6 | 3.0 | 2.8 | 2.8 | 2.6 | 2.0 | 2.4 | 2.4 | 2.4 | 2.3 |
| | 5. CCCMA CGCM3.1 | 0.9 | 0.9 | 0.9 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | l.5 | l.5 | 1.5 | 1.3 | l.3 | 1.3 | l.4 | 1.3 | l.4 | 2.1 | 2.1 | 2.1 | 1.9 | 1.8 | 1.8 | 1.8 | 1.8 | 1.9 |
| | 6. IPSL CM4 | 0.9 | 0.9 | 0.9 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 1.5 | 1.5 | 1.5 | 1.3 | 1.3 | 1.3 | 1.3 | 1.3 | 1.3 | 2.1 | 2.1 | 2.1 | 1.9 | 1.8 | 1.8 | 1.8 | 1.8 | 1.9 |
| | 7. GFDL CM2.0 | 0.9 | 0.9 | 0.9 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 1.5 | 1.5 | 1.5 | 1.4 | 1.3 | 1.3 | 1.3 | 1.3 | 1.3 | 2.1 | 2.1 | 2.1 | 1.9 | 1.8 | 1.8 | 1.8 | 1.8 | 1.9 |
| | 8. MEDRES MIROC3.2 | 0.9 | 0.9 | 0.9 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 1.5 | 1.5 | 1.5 | 1.4 | 1.3 | 1.3 | 1.3 | 1.3 | 1.3 | 2.1 | 2.1 | 2.1 | 1.9 | 1.8 | 1.8 | 1.8 | 1.8 | 1.9 |
| | 9. MIUB ECHO.G | 0.9 | 0.9 | 0.9 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 1.5 | 1.5 | 1.5 | 1.4 | 1.3 | 1.3 | 1.3 | 1.3 | 1.3 | 2.1 | 2.1 | 2.1 | 1.9 | 1.8 | 1.8 | 1.8 | 1.8 | 1.9 |
| | 10. MPI ECHAM5 | 0.9 | 0.9 | 1.0 | 0.8 | 0.7 | 0.8 | 0.8 | 0.8 | 0.8 | 1.5 | 1.5 | 1.6 | 1.3 | 1.2 | 1.3 | 1.2 | 1.2 | 1.3 | 2.1 | 2.1 | 2.2 | 1.9 | 1.7 | 1.8 | 1.7 | 1.7 | 1.9 |
| 2070 | 1. CSIRO MK3.5 | 1.8 | 1.7 | 1.7 | 1.6 | 1.2 | 1.4 | 1.4 | 1.4 | 1.4 | 3.0 | 2.8 | 2.8 | 2.6 | 1.9 | 2.3 | 2.3 | 2.3 | 2.3 | 4.7 | 4.4 | 4.4 | 4.3 | 3.0 | 3.7 | 3.7 | 3.6 | 3.7 |
| | 2. MRI CGCM2.3.2A | 1.7 | 1.6 | 1.6 | 1.5 | 1.2 | 1.4 | 1.4 | 1.4 | 1.3 | 2.8 | 2.6 | 2.6 | 2.5 | 1.9 | 2.2 | 2.2 | 2.2 | 2.1 | 4.4 | 4.1 | 4.1 | 4.0 | 3.0 | 3.5 | 3.5 | 3.5 | 3.4 |
| | 3. CSIRO MK3.0 | 1.7 | 1.6 | 1.6 | 1.5 | 1.2 | 1.4 | 1.4 | 1.4 | 1.3 | 2.8 | 2.6 | 2.6 | 2.5 | 1.9 | 2.2 | 2.2 | 2.2 | 2.1 | 4.4 | 4.1 | 4.1 | 4.0 | 3.0 | 3.5 | 3.5 | 3.5 | 3.4 |
| | 4. GFDL CM2.1 | 1.7 | 1.6 | 1.6 | 1.5 | 1.2 | 1.4 | 1.4 | 1.4 | 1.3 | 2.8 | 2.6 | 2.6 | 2.5 | 1.9 | 2.2 | 2.2 | 2.2 | 2.1 | 4.4 | 4.1 | 4.1 | 4.0 | 3.0 | 3.5 | 3.5 | 3.5 | 3.4 |
| | 5. CCCMA CGCM3.1 | 1.2 | 1.2 | 1.2 | 1.1 | 1.0 | 1.1 | 1.1 | 1.0 | 1.1 | 1.9 | 1.9 | 2.0 | 1.8 | 1.7 | 1.7 | 1.7 | 1.7 | 1.7 | 3.0 | 3.0 | 3.0 | 2.8 | 2.6 | 2.6 | 2.6 | 2.6 | 2.7 |
| | 6. IPSL CM4 | 1.2 | 1.2 | 1.2 | 1.1 | 1.0 | 1.1 | 1.0 | 1.0 | 1.1 | 1.9 | 1.9 | 2.0 | 1.8 | 1.7 | 1.7 | 1.7 | 1.7 | 1.7 | 3.0 | 3.1 | 3.1 | 2.9 | 2.6 | 2.7 | 2.7 | 2.6 | 2.8 |
| | 7. GFDL CM2.0 | 1.2 | 1.2 | 1.2 | 1.1 | 1.0 | 1.1 | 1.1 | 1.0 | 1.1 | 1.9 | 1.9 | 2.0 | 1.8 | 1.7 | 1.7 | 1.7 | 1.7 | 1.7 | 3.0 | 3.1 | 3.1 | 2.9 | 2.6 | 2.7 | 2.7 | 2.6 | 2.8 |
| | 8. MEDRES MIROC3.2 | 1.2 | 1.2 | 1.2 | 1.1 | 1.0 | 1.1 | 1.1 | 1.0 | 1.1 | 1.9 | 1.9 | 2.0 | 1.8 | 1.7 | 1.7 | 1.7 | 1.7 | 1.7 | 3.0 | 3.1 | 3.1 | 2.9 | 2.6 | 2.7 | 2.7 | 2.6 | 2.8 |
| | 9. MIUB ECHO.G | 1.2 | 1.2 | 1.2 | 1.1 | 1.0 | 1.1 | 1.1 | 1.0 | 1.1 | 1.9 | 1.9 | 2.0 | 1.8 | 1.7 | 1.7 | 1.7 | 1.7 | 1.7 | 3.0 | 3.1 | 3.1 | 2.9 | 2.6 | 2.7 | 2.7 | 2.6 | 2.8 |
| | 10. MPI ECHAM5 | 1.2 | 1.2 | 1.3 | 1.1 | 1.0 | 1.0 | 1.0 | 1.0 | 1.1 | 2.0 | 2.0 | 2.0 | 1.8 | 1.6 | 1.6 | 1.6 | 1.6 | 1.7 | 3.1 | 3.1 | 3.2 | 2.8 | 2.5 | 2.6 | 2.5 | 2.5 | 2.8 |

[†]Wine regions are numbered as they were appeared in Figure 4.1. SD = Swan District, PH = Perth Hills, PL = Peel, GR-Geographe, MR = Margaret River, BW = Blackwood Valley, MJ = Manjimup, PM = Pemberton, GS = Great Southern

### 4.3.2 Growing season average temperature

The highest average GST among the study regions is currently limited to 22.0°C in the Swan District, the northern part of the Perth Hills, and in the northwest of the Peel region (Figure 4.2). Under high warming range, these same northern regions are projected to have a GST of up to 23.5°C by 2030, which none of the WA wine regions are experiencing under the current climate. This projected GST warming continues reaching 22 to 26.5°C in the Swan District, Perth Hills and Peel regions, most of the Geographe and the northern parts of the Blackwood Valley regions by 2070 under high warming range (Table 4.3, Figure 4.2). By 2070, under high warming range, the GST range of 20.5 to 22.0°C, which is currently only dominant for the Swan District and northern part of the Perth Hills regions, will cover the entire southern regions including the Margaret River and southern parts of the Blackwood Valley regions.

GST warming rate is less intense under the low warming scenario. The overall current GST distribution is generally maintained until 2030, with some changes in scattered places across all the wine regions except the Pemberton and Manjimup regions (Figure 4.2). However, by 2050 current GST ranges will be completely replaced by a 1.5°C warmer GST range for the Swan District, Perth Hills, eastern parts of the Peel, southern parts of the Geographe, northern parts of the Blackwood Valley, and entire areas of the Margaret River region. Under low warming climate change range, the largest changes in the average GST will be a 1.5°C warmer GST range for the northern and central wine regions by the 2050 and 2070 periods (Figure 4.2; Table 4.3). On the other hand, the GST warming will be less marked in the southern regions, except the northern parts of the Great Southern region, which will experience a 1.5°C warmer GST above the current 17.5 to 19.0°C range.

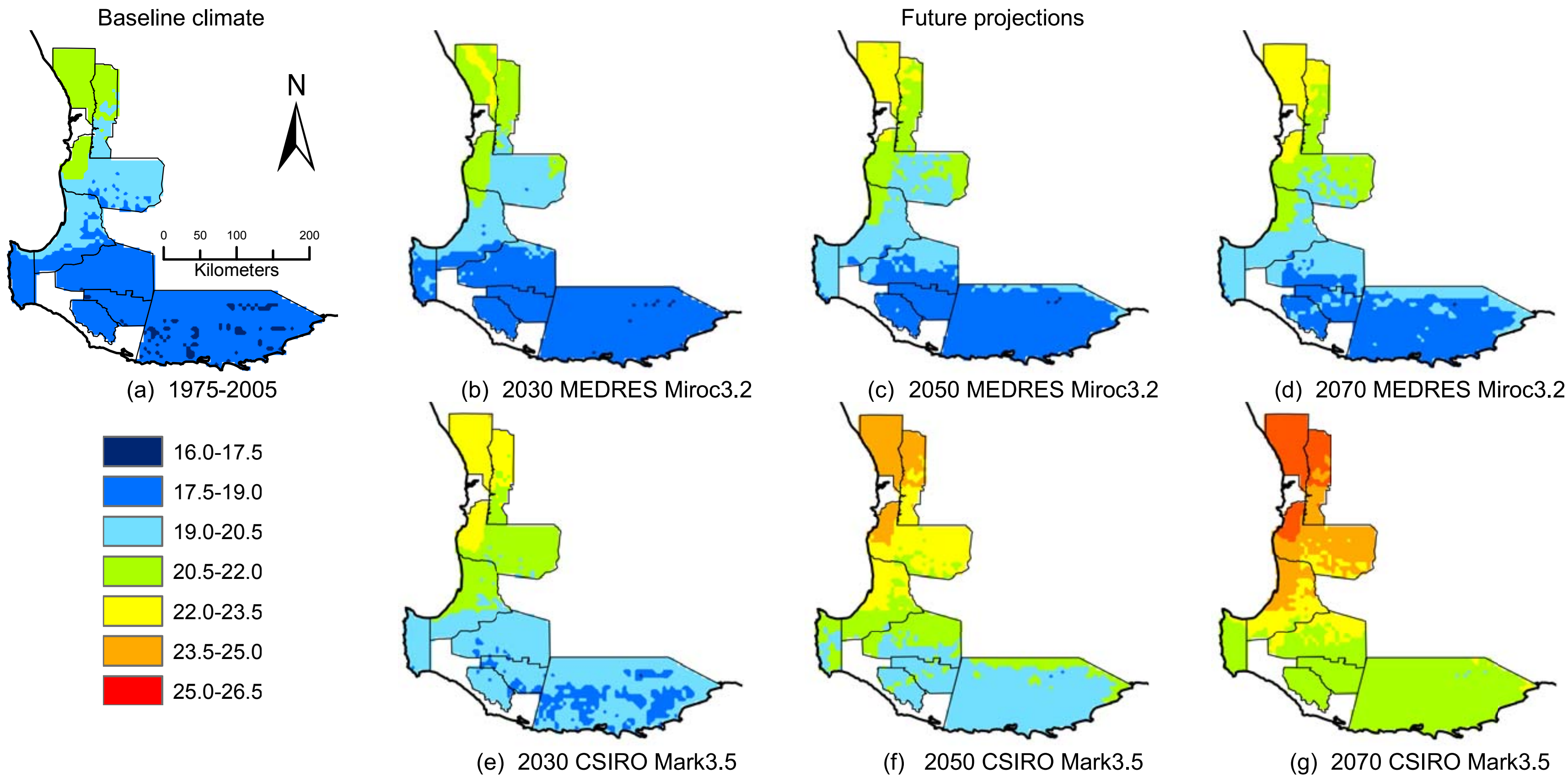


Figure 4.2 Current and projected average temperature (°C) during October to April under SRES A2 emission scenario

Table 4.3 Current and projected average October to April and mean January temperature (MJT) under SRES A2 emission scenario

| Year and Climate model | Statistics | October to April mean temperature (°C) | | | | | | | | | MJT (°C) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | †Wine regions | | | | | | | | | | | | | | | | | |
| | | SD | PH | PL | GR | MR | BW | MJ | PM | GS | SD | PH | PL | GR | MR | BW | MJ | PM | GS |
| 1990 | Minimum | 21.0 | 19.5 | 18.5 | 17.8 | 17.7 | 17.4 | 17.3 | 17.5 | 16.0 | 23.7 | 22.9 | 21.9 | 20.6 | 19.2 | 20.0 | 19.5 | 19.6 | 18.3 |
| | Quartile 1 | 21.3 | 20.3 | 19.3 | 18.7 | 18.4 | 18.0 | 17.7 | 17.7 | 17.6 | 24.1 | 23.5 | 22.8 | 21.8 | 20.2 | 20.8 | 20.0 | 19.8 | 19.4 |
| | Median | 21.4 | 20.7 | 19.6 | 19.1 | 18.6 | 18.3 | 17.8 | 17.9 | 17.8 | 24.4 | 24.1 | 23.1 | 22.2 | 20.4 | 21.2 | 20.3 | 19.9 | 19.7 |
| | Quartile 2 | 21.6 | 21.1 | 20.2 | 19.5 | 18.7 | 18.5 | 18.0 | 17.9 | 18.0 | 24.6 | 24.5 | 23.3 | 22.5 | 20.7 | 21.6 | 20.4 | 20.1 | 20.2 |
| | Maximum | 21.8 | 21.7 | 21.2 | 20.3 | 19.2 | 18.9 | 18.2 | 18.4 | 18.6 | 25.1 | 25.0 | 24.2 | 23.2 | 21.6 | 22.1 | 20.9 | 20.6 | 21.0 |
| | Average | 21.4 | 20.6 | 19.7 | 19.1 | 18.6 | 18.2 | 17.8 | 17.9 | 17.8 | 24.4 | 24.0 | 23.1 | 22.1 | 20.5 | 21.2 | 20.3 | 19.9 | 19.8 |
| 2030 MEDRES Miroc3.2 | Minimum | 21.5 | 20.0 | 19.0 | 18.2 | 18.1 | 17.9 | 17.8 | 17.9 | 16.4 | 24.0 | 23.3 | 22.3 | 20.9 | 19.5 | 20.4 | 19.8 | 19.9 | 18.7 |
| | Quartile 1 | 21.8 | 20.8 | 19.8 | 19.2 | 18.8 | 18.4 | 18.1 | 18.1 | 18.0 | 24.5 | 23.9 | 23.2 | 22.1 | 20.5 | 21.1 | 20.4 | 20.1 | 19.7 |
| | Median | 21.9 | 21.2 | 20.1 | 19.6 | 18.9 | 18.7 | 18.2 | 18.3 | 18.2 | 24.8 | 24.4 | 23.5 | 22.5 | 20.7 | 21.5 | 20.6 | 20.2 | 20.1 |
| | Quartile 2 | 22.0 | 21.6 | 20.7 | 19.9 | 19.1 | 18.9 | 18.4 | 18.3 | 18.4 | 25.0 | 24.9 | 23.8 | 22.9 | 21.0 | 21.9 | 20.8 | 20.4 | 20.6 |
| | Maximum | 22.3 | 22.1 | 21.7 | 20.8 | 19.6 | 19.3 | 18.6 | 18.8 | 19.0 | 25.4 | 25.4 | 24.6 | 23.6 | 22.0 | 22.4 | 21.2 | 20.9 | 21.3 |
| | Average | 21.9 | 21.1 | 20.3 | 19.6 | 19.0 | 18.7 | 18.2 | 18.3 | 18.2 | 24.7 | 24.4 | 23.5 | 22.5 | 20.8 | 21.5 | 20.6 | 20.3 | 20.1 |
| 2050 MEDRES Miroc3.2 | Minimum | 21.9 | 20.4 | 19.4 | 18.6 | 18.5 | 18.2 | 18.1 | 18.3 | 16.8 | 24.5 | 23.7 | 22.7 | 21.3 | 19.8 | 20.7 | 20.1 | 20.3 | 19.1 |
| | Quartile 1 | 22.2 | 21.2 | 20.3 | 19.5 | 19.2 | 18.8 | 18.4 | 18.5 | 18.4 | 24.9 | 24.3 | 23.6 | 22.4 | 20.9 | 21.4 | 20.7 | 20.4 | 20.1 |
| | Median | 22.3 | 21.6 | 20.6 | 20.0 | 19.3 | 19.1 | 18.6 | 18.6 | 18.6 | 25.2 | 24.9 | 23.9 | 22.9 | 21.1 | 21.9 | 21.0 | 20.6 | 20.5 |
| | Quartile 2 | 22.5 | 22.0 | 21.4 | 20.4 | 19.5 | 19.3 | 18.7 | 18.7 | 18.8 | 25.4 | 25.3 | 24.3 | 23.3 | 21.3 | 22.3 | 21.1 | 20.7 | 21.0 |
| | Maximum | 22.7 | 22.6 | 22.1 | 21.2 | 20.0 | 19.7 | 19.0 | 19.1 | 19.4 | 25.8 | 25.8 | 25.1 | 24.0 | 22.3 | 22.8 | 21.5 | 21.3 | 21.7 |
| | Average | 22.4 | 21.6 | 20.8 | 20.0 | 19.3 | 19.0 | 18.6 | 18.6 | 18.6 | 25.2 | 24.8 | 23.9 | 22.8 | 21.1 | 21.9 | 20.9 | 20.6 | 20.5 |
| 2070 MEDRES Miroc3.2 | Minimum | 22.2 | 20.7 | 19.7 | 18.8 | 18.7 | 18.4 | 18.3 | 18.5 | 17.1 | 24.7 | 24.0 | 23.0 | 21.5 | 20.1 | 20.9 | 20.4 | 20.5 | 19.3 |
| | Quartile 1 | 22.5 | 21.5 | 20.6 | 19.8 | 19.4 | 19.0 | 18.7 | 18.7 | 18.7 | 25.2 | 24.6 | 23.9 | 22.7 | 21.1 | 21.7 | 21.0 | 20.7 | 20.4 |
| | Median | 22.6 | 21.9 | 20.9 | 20.2 | 19.5 | 19.3 | 18.8 | 18.9 | 18.8 | 25.5 | 25.1 | 24.2 | 23.2 | 21.3 | 22.1 | 21.2 | 20.8 | 20.7 |
| | Quartile 2 | 22.8 | 22.3 | 21.7 | 20.7 | 19.7 | 19.5 | 19.0 | 18.9 | 19.1 | 25.7 | 25.5 | 24.6 | 23.6 | 21.6 | 22.5 | 21.4 | 21.0 | 21.2 |
| | Maximum | 23.0 | 22.9 | 22.4 | 21.5 | 20.2 | 20.0 | 19.2 | 19.4 | 19.6 | 26.1 | 26.1 | 25.6 | 24.3 | 22.5 | 23.1 | 21.8 | 21.5 | 22.0 |
| | Average | 22.6 | 21.9 | 21.1 | 20.2 | 19.6 | 19.3 | 18.8 | 18.9 | 18.8 | 25.4 | 25.1 | 24.2 | 23.1 | 21.4 | 22.1 | 21.2 | 20.8 | 20.8 |
| 2030 CSIRO Mk3.5 | Minimum | 22.8 | 21.1 | 20.1 | 19.2 | 18.8 | 18.8 | 18.7 | 18.9 | 17.4 | 25.3 | 24.5 | 23.5 | 21.8 | 20.1 | 21.2 | 20.7 | 20.8 | 19.5 |
| | Quartile 1 | 23.0 | 21.9 | 20.9 | 20.2 | 19.5 | 19.3 | 19.0 | 19.1 | 19.0 | 25.7 | 25.1 | 24.3 | 23.0 | 21.2 | 22.0 | 21.3 | 21.0 | 20.6 |
| | Median | 23.1 | 22.4 | 21.2 | 20.7 | 19.7 | 19.7 | 19.2 | 19.2 | 19.1 | 26.0 | 25.6 | 24.6 | 23.7 | 21.4 | 22.4 | 21.5 | 21.1 | 20.9 |
| | Quartile 2 | 23.3 | 22.8 | 21.8 | 21.1 | 19.8 | 19.8 | 19.3 | 19.3 | 19.3 | 26.3 | 26.1 | 24.8 | 24.0 | 21.7 | 22.8 | 21.7 | 21.3 | 21.4 |
| | Maximum | 23.5 | 23.4 | 22.8 | 21.9 | 20.4 | 20.2 | 19.5 | 19.7 | 19.9 | 26.7 | 26.7 | 25.7 | 24.7 | 22.6 | 23.3 | 22.1 | 21.8 | 22.2 |
| | Average | 23.1 | 22.3 | 21.4 | 20.7 | 19.7 | 19.6 | 19.2 | 19.2 | 19.1 | 26.0 | 25.6 | 24.6 | 23.5 | 21.5 | 22.4 | 21.5 | 21.2 | 21.0 |
| 2050 CSIRO Mk3.5 | Minimum | 24.1 | 22.5 | 21.5 | 20.3 | 19.7 | 19.9 | 19.8 | 20.0 | 18.5 | 26.7 | 25.8 | 24.8 | 22.9 | 21.0 | 22.3 | 21.7 | 21.9 | 20.6 |
| | Quartile 1 | 24.4 | 23.2 | 22.3 | 21.4 | 20.4 | 20.4 | 20.1 | 20.2 | 20.1 | 27.2 | 26.4 | 25.6 | 24.1 | 22.1 | 23.0 | 22.3 | 22.1 | 21.6 |
| | Median | 24.6 | 23.7 | 22.5 | 22.0 | 20.6 | 20.8 | 20.3 | 20.3 | 20.2 | 27.5 | 26.9 | 25.9 | 25.0 | 22.3 | 23.5 | 22.6 | 22.2 | 22.0 |
| | Quartile 2 | 24.7 | 24.2 | 23.1 | 22.4 | 20.7 | 20.9 | 20.4 | 20.4 | 20.5 | 27.7 | 27.5 | 26.2 | 25.3 | 22.5 | 23.9 | 22.7 | 22.3 | 22.5 |
| | Maximum | 25.0 | 24.8 | 24.2 | 23.2 | 21.4 | 21.3 | 20.7 | 20.8 | 21.0 | 28.2 | 28.2 | 27.0 | 26.0 | 23.5 | 24.4 | 23.1 | 22.9 | 23.3 |
| | Average | 24.6 | 23.7 | 22.7 | 21.9 | 20.6 | 20.7 | 20.3 | 20.3 | 20.2 | 27.4 | 27.0 | 25.9 | 24.8 | 22.3 | 23.5 | 22.5 | 22.2 | 22.1 |
| 2070 CSIRO Mk3.5 | Minimum | 25.6 | 23.9 | 22.9 | 21.5 | 20.7 | 21.1 | 21.0 | 21.2 | 19.7 | 28.1 | 27.2 | 26.2 | 24.0 | 22.0 | 23.4 | 22.9 | 23.0 | 21.7 |
| | Quartile 1 | 26.0 | 24.7 | 23.7 | 22.5 | 21.4 | 21.6 | 21.3 | 21.4 | 21.3 | 28.7 | 27.8 | 27.1 | 25.2 | 23.0 | 24.2 | 23.5 | 23.2 | 22.8 |
| | Median | 26.1 | 25.1 | 24.0 | 23.4 | 21.5 | 22.0 | 21.5 | 21.5 | 21.4 | 29.0 | 28.4 | 27.3 | 26.5 | 23.2 | 24.6 | 23.7 | 23.3 | 23.1 |
| | Quartile 2 | 26.2 | 25.7 | 24.5 | 23.8 | 21.7 | 22.1 | 21.6 | 21.6 | 21.7 | 29.3 | 29.1 | 27.6 | 26.8 | 23.5 | 25.0 | 23.9 | 23.5 | 23.6 |
| | Maximum | 26.5 | 26.4 | 25.6 | 24.7 | 22.5 | 22.5 | 21.8 | 22.0 | 22.2 | 29.8 | 29.7 | 28.5 | 27.5 | 24.4 | 25.5 | 24.3 | 24.0 | 24.4 |
| | Average | 26.1 | 25.2 | 24.1 | 23.2 | 21.6 | 21.9 | 21.5 | 21.5 | 21.4 | 29.0 | 28.5 | 27.3 | 26.1 | 23.3 | 24.6 | 23.7 | 23.4 | 23.2 |

†Wine regions: SD = Swan District, PH = Perth Hills, PL = Peel, GR-Geographe, MR = Margaret River, BW = Blackwood Valley, MJ = Manjimup, PM = Pemberton, GS = Great Southern

Climate projections also indicate that increases in average GST, compared to the current climate condition will be region specific. For example, the magnitude of future GST increases is projected to be consistently lower in the Margaret River region, even under high warming range, whereas the Swan District and Perth Hills regions are likely to experience higher warming in terms of GST increase. This would indicate potential uneven impacts of climate change on viticulture across the WA wine regions.

### 4.3.3 Mean January temperature

Currently, MJT averages across the study wine regions vary between 24.4°C in the northern Swan District to 19.8°C in the Great Southern region, however, under future climate change these averages are likely to increase with time. By 2050, under high warming range, current patterns of MJT will be completely overtaken by as much as a 3.1°C increase across the wine regions (Figure 4.3; Table 4.3). Furthermore, by 2070 the majority of the currently cooler Great Southern region will fall under a 22 to 23.5°C temperature range, which at present covers only most of the Peel and northern half of the Geographe regions (Figure 4.3). Spatially, the greatest increases in MJT are projected to occur in the northern regions. Entire areas of the northern regions, and most of the northern part of the Geographe region will have a MJT between 26.5 and 29.5°C, which is at least 2.2 to 4.6°C warmer than the currently hottest MJT in the Swan District and Perth Hills regions (Figure 4.3).

Patterns of MJT warming under low warming range are similar to that of high warming range, although the magnitudes are less. For example, by 2070, most of the regions will have a warmer MJT with the greatest increases being about 1°C for the Great Southern, followed by the Pemberton and Peel regions. However, the current MJT pattern will remain the same for some areas throughout the time periods examined in this study. For example, southern parts of the Great Southern and the northwest corner of the Peel regions will be unchanged if future climate change develops under low warming conditions assumed for this study.

### 4.3.4 Grape maturity period average temperature

The average temperature during grape maturity (February to March for this study) will be at least 1.1 to 1.7°C warmer by 2030 across all the WA wine regions under high warming range (Table 4.4; Figure 4.4). By 2050 the warming progresses further, reaching 2.0 to 3.3°C, the latter applying mostly to the northern wine regions (Figure 4.4). The three northern regions and the Geographe region will likely experience the greatest warming during the

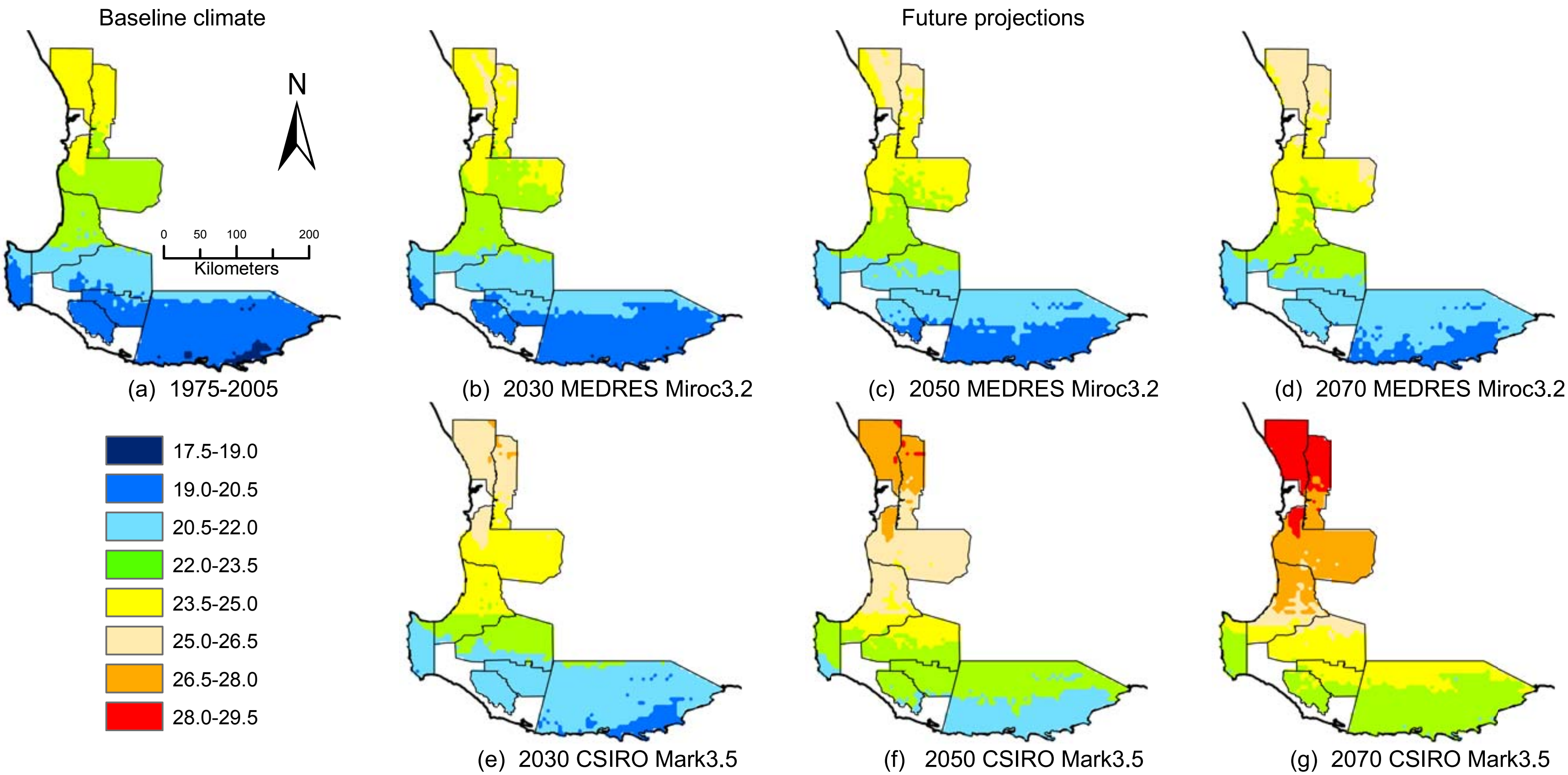


Figure 4.3 Current and projected Mean January Temperature (°C) under SRES A2 emission scenario

grape maturity period compared to the southern regions across the time frames examined (Table 4.4). Of these, by 2070 the Swan District is projected to achieve the maximum warming of 4.9°C over its current value of 23.4°C, while the lowest increase is likely to be 3.0 to 3.8°C for the Margaret River and the southern regions (Table 4.4; Figure 4.4).

The grape maturity period warming is projected to be less intense under low warming range. The current average temperature will likely remain much the same for the Swan District, Great Southern, Pemberton, and Manjimup regions until 2030. Some areas, for example, the northern parts of the Perth Hills, Peel, and the central and southern parts of the Margaret River region might have warmer average temperatures during the grape maturity period under climate change (Figure 4.4b). This warming continues with time producing a southward shift of current temperature patterns (Figure 4.4c, d). However, the maximum warming that is likely to happen under low warming range is projected to be less than 1.5°C across the regions at least until 2070 (Figure 4.4; Table 4.4).

### 4.3.5 Projected non-growing season temperature

Under the current climate, the lowest average temperature during May to September is in the Blackwood Valley with an average of 11.3°C, while the warmest is in the Swan District averaging 14.2°C (Table 4.4). These averages are projected to increase with about 0.5°C warming per decade reaching 14.2°C and 17.7°C, respectively for the above regions, under high warming climate change by 2070 (Table 4.4; Figure 4.5). Under this climate change range, the northern wine districts and the Geographe region are projected more warming compared to the other regions (Table 4.4).

Table 4.4 Current and projected average temperature for February to March and May to September period under SRES A2 emission scenario

| Year and Climate model | Statistics | Feb to March mean temperature (°C) | | | | | | | | | May to September average temperature | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | [†]Wine regions | | | | | | | | | | | | | | | | | |
| | | SD | PH | PL | GR | MR | BW | MJ | PM | GS | SD | PH | PL | GR | MR | BW | MJ | PM | GS |
| 1990 | Minimum | 23.5 | 22.0 | 20.9 | 20.1 | 19.4 | 19.6 | 19.3 | 19.5 | 17.9 | 13.1 | 11.5 | 10.4 | 10.8 | 12.9 | 10.8 | 11.2 | 11.8 | 9.8 |
| | Quartile 1 | 23.8 | 22.8 | 21.7 | 21.1 | 20.3 | 20.1 | 19.7 | 19.7 | 19.4 | 13.9 | 12.2 | 11.2 | 11.6 | 13.5 | 11.1 | 11.6 | 12.2 | 11.7 |
| | Median | 23.9 | 23.3 | 22.0 | 21.5 | 20.4 | 20.5 | 19.9 | 19.8 | 19.6 | 14.3 | 12.6 | 11.4 | 12.2 | 13.8 | 11.2 | 11.8 | 12.5 | 12.1 |
| | Quartile 2 | 24.1 | 23.7 | 22.6 | 21.9 | 20.7 | 20.8 | 20.0 | 19.9 | 19.8 | 14.5 | 12.9 | 13.1 | 13.1 | 14.1 | 11.4 | 11.9 | 12.8 | 12.7 |
| | Maximum | 24.4 | 24.2 | 23.8 | 22.7 | 21.3 | 21.2 | 20.3 | 20.4 | 20.4 | 15.0 | 13.6 | 14.6 | 14.1 | 14.4 | 12.7 | 12.4 | 13.1 | 13.7 |
| | Average | 23.9 | 23.2 | 22.2 | 21.5 | 20.5 | 20.5 | 19.9 | 19.8 | 19.6 | 14.2 | 12.6 | 12.0 | 12.3 | 13.8 | 11.3 | 11.7 | 12.5 | 12.2 |
| 2030 MEDRES Miroc3.2 | Minimum | 23.9 | 22.4 | 21.3 | 20.5 | 19.8 | 19.9 | 19.6 | 19.8 | 18.3 | 13.3 | 11.7 | 10.6 | 11.0 | 13.0 | 11.0 | 11.3 | 11.9 | 9.9 |
| | Quartile 1 | 24.2 | 23.2 | 22.1 | 21.5 | 20.6 | 20.5 | 20.0 | 20.0 | 19.7 | 14.1 | 12.4 | 11.4 | 11.8 | 13.7 | 11.2 | 11.7 | 12.3 | 11.8 |
| | Median | 24.3 | 23.7 | 22.5 | 21.9 | 20.8 | 20.8 | 20.2 | 20.1 | 19.9 | 14.5 | 12.7 | 11.7 | 12.3 | 14.0 | 11.4 | 11.9 | 12.6 | 12.3 |
| | Quartile 2 | 24.5 | 24.1 | 23.0 | 22.2 | 21.0 | 21.1 | 20.3 | 20.2 | 20.2 | 14.7 | 13.1 | 13.3 | 13.2 | 14.2 | 11.5 | 12.0 | 12.9 | 12.8 |
| | Maximum | 24.8 | 24.6 | 24.2 | 23.1 | 21.6 | 21.5 | 20.6 | 20.7 | 20.8 | 15.2 | 13.8 | 14.8 | 14.3 | 14.6 | 12.9 | 12.5 | 13.3 | 13.9 |
| | Average | 24.3 | 23.6 | 22.6 | 21.9 | 20.8 | 20.8 | 20.2 | 20.2 | 20.0 | 14.4 | 12.8 | 12.3 | 12.5 | 13.9 | 11.5 | 11.9 | 12.6 | 12.3 |
| 2050 MEDRES Miroc3.2 | Minimum | 24.3 | 22.8 | 21.8 | 20.8 | 20.1 | 20.3 | 20.0 | 20.2 | 18.7 | 14.4 | 12.7 | 11.7 | 11.8 | 13.9 | 11.9 | 12.2 | 12.8 | 10.8 |
| | Quartile 1 | 24.6 | 23.6 | 22.6 | 21.8 | 21.0 | 20.8 | 20.4 | 20.4 | 20.1 | 15.1 | 13.4 | 12.5 | 12.8 | 14.6 | 12.1 | 12.6 | 13.2 | 12.7 |
| | Median | 24.7 | 24.1 | 22.9 | 22.2 | 21.1 | 21.2 | 20.6 | 20.5 | 20.3 | 15.5 | 13.8 | 12.9 | 13.3 | 14.9 | 12.2 | 12.8 | 13.5 | 13.1 |
| | Quartile 2 | 24.9 | 24.5 | 23.6 | 22.7 | 21.4 | 21.4 | 20.7 | 20.6 | 20.6 | 15.8 | 14.1 | 14.4 | 14.2 | 15.1 | 12.4 | 12.9 | 13.8 | 13.7 |
| | Maximum | 25.2 | 25.0 | 24.6 | 23.5 | 21.9 | 21.9 | 21.0 | 21.1 | 21.1 | 16.2 | 14.8 | 15.9 | 15.3 | 15.5 | 13.8 | 13.4 | 14.1 | 14.8 |
| | Average | 24.8 | 24.0 | 23.1 | 22.2 | 21.2 | 21.2 | 20.5 | 20.5 | 20.4 | 15.4 | 13.8 | 13.4 | 13.5 | 14.8 | 12.3 | 12.8 | 13.5 | 13.2 |
| 2070 MEDRES Miroc3.2 | Minimum | 24.6 | 23.1 | 22.0 | 21.1 | 20.3 | 20.5 | 20.2 | 20.4 | 18.9 | 15.1 | 13.5 | 12.5 | 12.5 | 14.5 | 12.5 | 12.9 | 13.4 | 11.4 |
| | Quartile 1 | 24.9 | 23.9 | 22.9 | 22.0 | 21.2 | 21.1 | 20.6 | 20.6 | 20.4 | 15.9 | 14.2 | 13.3 | 13.6 | 15.2 | 12.7 | 13.2 | 13.8 | 13.4 |
| | Median | 25.0 | 24.4 | 23.2 | 22.5 | 21.3 | 21.4 | 20.8 | 20.7 | 20.6 | 16.3 | 14.6 | 13.7 | 13.9 | 15.4 | 12.9 | 13.4 | 14.1 | 13.8 |
| | Quartile 2 | 25.2 | 24.8 | 24.0 | 22.9 | 21.6 | 21.7 | 20.9 | 20.8 | 20.8 | 16.5 | 14.9 | 15.2 | 14.9 | 15.7 | 13.1 | 13.5 | 14.4 | 14.4 |
| | Maximum | 25.5 | 25.3 | 24.9 | 23.8 | 22.2 | 22.1 | 21.2 | 21.3 | 21.4 | 17.0 | 15.6 | 16.6 | 16.1 | 16.0 | 14.4 | 14.0 | 14.8 | 15.4 |
| | Average | 25.0 | 24.3 | 23.4 | 22.5 | 21.4 | 21.4 | 20.8 | 20.8 | 20.6 | 16.2 | 14.6 | 14.3 | 14.2 | 15.4 | 13.0 | 13.4 | 14.1 | 13.9 |
| 2030 CSIRO Mk3.5 | Minimum | 25.3 | 23.6 | 22.6 | 21.5 | 20.5 | 20.9 | 20.6 | 20.8 | 19.3 | 14.2 | 12.4 | 11.4 | 11.7 | 13.6 | 11.7 | 12.0 | 12.6 | 10.6 |
| | Quartile 1 | 25.5 | 24.5 | 23.4 | 22.5 | 21.4 | 21.5 | 21.0 | 21.1 | 20.7 | 14.9 | 13.2 | 12.1 | 12.6 | 14.3 | 11.9 | 12.4 | 13.1 | 12.5 |
| | Median | 25.7 | 25.0 | 23.6 | 23.1 | 21.5 | 21.8 | 21.2 | 21.2 | 20.9 | 15.3 | 13.6 | 12.3 | 13.1 | 14.6 | 12.1 | 12.6 | 13.3 | 13.0 |
| | Quartile 2 | 25.9 | 25.4 | 24.2 | 23.5 | 21.8 | 22.1 | 21.4 | 21.2 | 21.2 | 15.6 | 13.9 | 14.1 | 14.0 | 14.8 | 12.2 | 12.8 | 13.6 | 13.5 |
| | Maximum | 26.1 | 26.0 | 25.4 | 24.4 | 22.4 | 22.5 | 21.6 | 21.7 | 21.7 | 16.1 | 14.6 | 15.5 | 15.0 | 15.3 | 13.6 | 13.2 | 14.0 | 14.6 |
| | Average | 25.7 | 24.9 | 23.8 | 23.0 | 21.6 | 21.8 | 21.2 | 21.2 | 20.9 | 15.2 | 13.6 | 13.0 | 13.3 | 14.5 | 12.2 | 12.6 | 13.3 | 13.1 |
| 2050 CSIRO Mk3.5 | Minimum | 26.7 | 25.0 | 24.0 | 22.6 | 21.4 | 22.1 | 21.8 | 22.0 | 20.4 | 15.4 | 13.5 | 12.4 | 12.7 | 14.5 | 12.6 | 13.0 | 13.6 | 11.6 |
| | Quartile 1 | 27.0 | 25.9 | 24.8 | 23.7 | 22.3 | 22.6 | 22.2 | 22.2 | 21.9 | 16.0 | 14.3 | 13.2 | 13.6 | 15.2 | 12.9 | 13.4 | 14.0 | 13.5 |
| | Median | 27.2 | 26.4 | 25.1 | 24.5 | 22.4 | 23.0 | 22.4 | 22.3 | 22.1 | 16.4 | 14.7 | 13.4 | 14.1 | 15.4 | 13.0 | 13.6 | 14.3 | 13.9 |
| | Quartile 2 | 27.4 | 27.0 | 25.6 | 24.9 | 22.7 | 23.3 | 22.5 | 22.4 | 22.3 | 16.8 | 15.0 | 15.2 | 15.1 | 15.7 | 13.2 | 13.7 | 14.6 | 14.6 |
| | Maximum | 27.7 | 27.6 | 26.8 | 25.8 | 23.5 | 23.7 | 22.8 | 22.9 | 22.9 | 17.3 | 15.8 | 16.6 | 16.1 | 16.2 | 14.6 | 14.2 | 15.0 | 15.6 |
| | Average | 27.2 | 26.4 | 25.2 | 24.3 | 22.5 | 23.0 | 22.4 | 22.3 | 22.1 | 16.4 | 14.7 | 14.0 | 14.3 | 15.4 | 13.1 | 13.6 | 14.3 | 14.1 |
| 2070 CSIRO Mk3.5 | Minimum | 28.2 | 26.6 | 25.5 | 23.9 | 22.5 | 23.3 | 23.1 | 23.2 | 21.7 | 16.6 | 14.7 | 13.6 | 13.7 | 15.4 | 13.7 | 14.1 | 14.6 | 12.7 |
| | Quartile 1 | 28.7 | 27.4 | 26.3 | 24.9 | 23.3 | 23.9 | 23.4 | 23.5 | 23.2 | 17.3 | 15.5 | 14.3 | 14.8 | 16.1 | 13.9 | 14.4 | 15.1 | 14.6 |
| | Median | 28.9 | 27.9 | 26.6 | 26.0 | 23.5 | 24.3 | 23.6 | 23.6 | 23.3 | 17.7 | 15.9 | 14.6 | 15.2 | 16.4 | 14.1 | 14.7 | 15.3 | 15.0 |
| | Quartile 2 | 29.0 | 28.6 | 27.1 | 26.4 | 23.7 | 24.5 | 23.8 | 23.7 | 23.6 | 18.1 | 16.3 | 16.3 | 16.2 | 16.6 | 14.3 | 14.8 | 15.6 | 15.6 |
| | Maximum | 29.3 | 29.2 | 28.3 | 27.3 | 24.6 | 24.9 | 24.0 | 24.1 | 24.1 | 18.6 | 17.1 | 17.8 | 17.3 | 17.2 | 15.6 | 15.3 | 16.0 | 16.7 |
| | Average | 28.8 | 28.0 | 26.7 | 25.8 | 23.5 | 24.2 | 23.6 | 23.6 | 23.4 | 17.7 | 15.9 | 15.2 | 15.4 | 16.3 | 14.2 | 14.6 | 15.4 | 15.1 |

[†]Wine regions: SD = Swan District, PH = Perth Hills, PL = Peel, GR-Geographe, MR = Margaret River, BW = Blackwood Valley, MJ = Manjimup, PM = Pemberton, GS = Great Southern

The current spatial distribution of the non-growing season average temperature is projcetd is projected to change completely across the study regions by 2050. The present non-growing season temperature of 14 to 15.5°C in the Swan District will likely prevail in the majority of the Great Southern, Manjimup, inland parts of the Geographe and Peel regions by 2070 under high warming range (Figure 4.5).

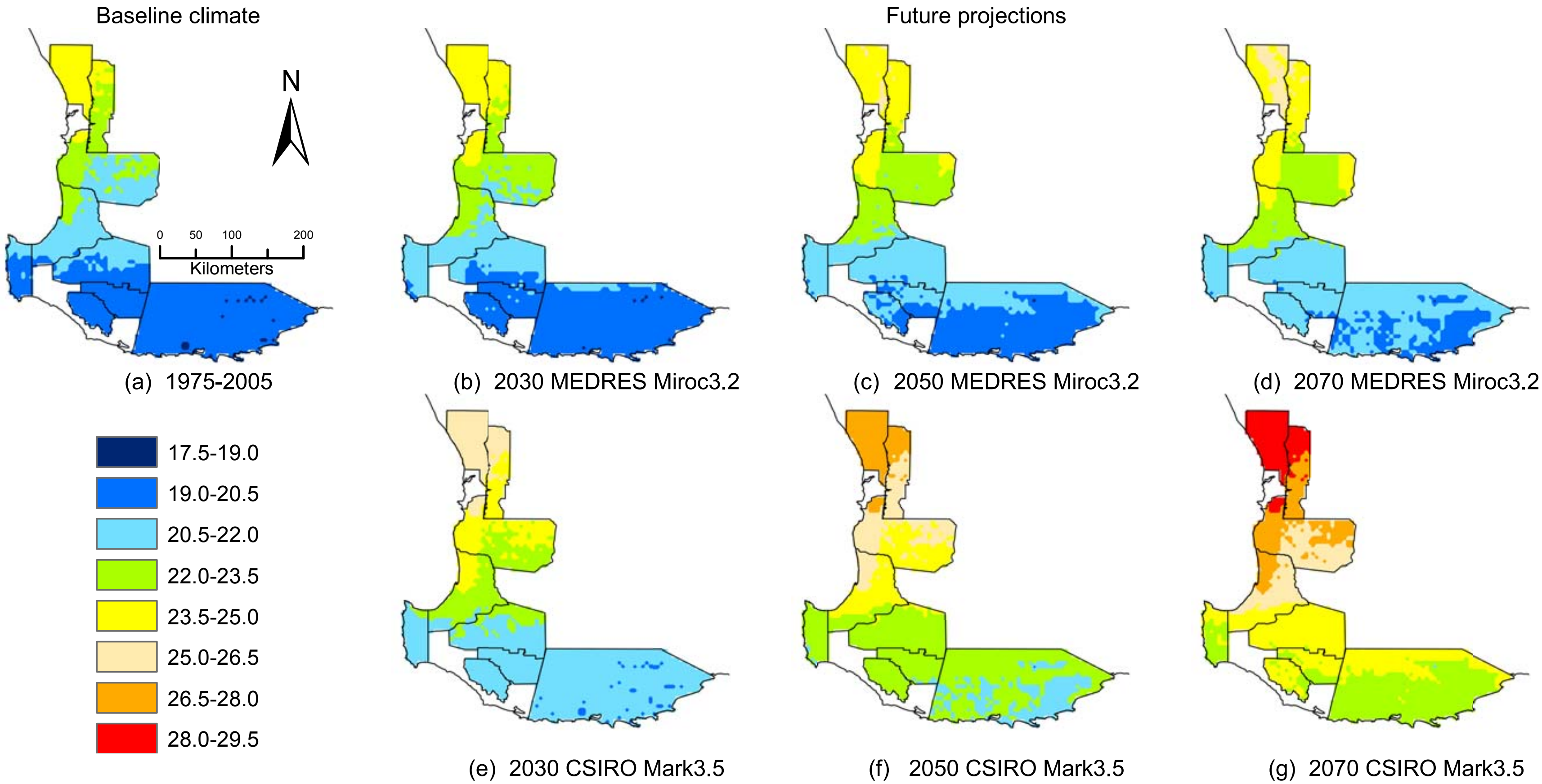


Figure 4.4 Current and projected average temperature during February to March (°C) under SRES A2 emission scenario

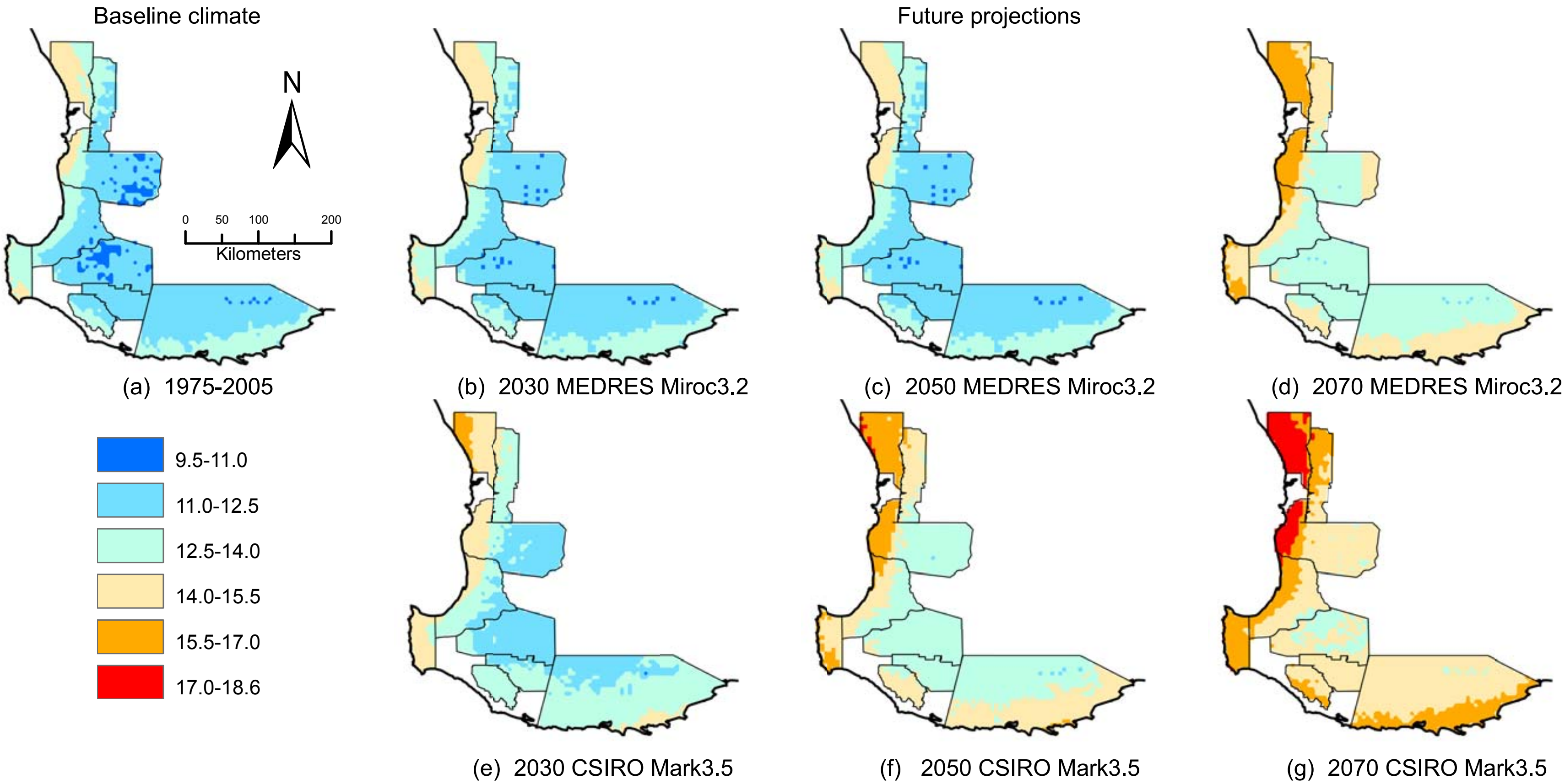


Figure 4.5 Current and projected average temperature during May to September (°C) under SRES A2 emission scenario

On the other hand, averaged across regions, about 0.2°C and 1.1°C warmer non-growing season temperatures are projected under low warming range by 2030 and 2050, respectively. With this low warming range, the Peel region is projected to experience the most warming of 1.4 and 2.3°C by 2050 and 2070, whilst the Margaret River is projected to have experience the smallest changes in the non-growing season average temperature under warming of 1.6°C by 2070 (Table 4.4). The northern wine regions are projected to experience slightly more warming in the non-growing season average temperature compared with the central and the southern regions under low warming range (Table 4.4).

### 4.3.6 Temperature variability during grape maturity

Averaged across the grape maturity period, changes in future daily temperature variability is small for the study regions, indicating similar magnitudes of increases in both daily minimum and maximum temperatures (Table 4.5; Figure 4.6). The most notable changes were for the inland parts of the Peel, Geographe, and northwest Blackwood Valley regions with a gradual decrease in the temperature variability index of about 100 units under low warming climate change range (Figure 4.6; Table 4.5). In contrast, the northern part of the Perth Hills region is projected to have a gradually increasing temperature variability of about 100 units under high warming range (Figure 4.6; Table 4.5).

### 4.3.7 Changes in growing degree days

Average GDDs among the study regions range between 1600 units (in the southern regions) and 2400 units (in the northern regions) during the grape growing season. These are likely to reach at least 2400 units in the southern regions and 3400 units in the northern regions by 2070 under high warming climate change range (Figure 4.7; Table 4.6). In terms of percentage, the changes in GDD are projected to be slightly higher in southern regions compared to northern regions. For example, the Great Southern region is projected to have 47% higher average GDD by 2070 under high warming scenario, while the currently warmest Swan District is projected to 41% increase in the GDD during the grape growing season. Projected increases in average GDDs under low warming ranges are 3- to 3.5-times less than what have been projected under high warming range (Table 4.6).

Table 4.5 Current and projected diurnal range during February to March under SRES A2 emission scenario

| **Year and Climate model** | **Statistics** | **SD** | **PH** | **PL** | **GR** | **MR** | **BW** | **MJ** | **PM** | **GS** |
|---|---|---|---|---|---|---|---|---|---|---|
| | | **†Wine regions** | | | | | | | | |
| 1990 | Minimum | 719 | 805 | 681 | 714 | 471 | 744 | 716 | 654 | 367 |
| | Quartile 1 | 768 | 851 | 808 | 792 | 556 | 835 | 759 | 683 | 579 |
| | Median | 818 | 876 | 890 | 844 | 607 | 870 | 777 | 708 | 670 |
| | Quartile 2 | 858 | 887 | 912 | 886 | 647 | 896 | 797 | 729 | 737 |
| | Maximum | 913 | 914 | 927 | 924 | 735 | 921 | 823 | 765 | 813 |
| | Average | 812 | 868 | 858 | 839 | 605 | 864 | 776 | 707 | 656 |
| 2030 MEDRES | Minimum | 718 | 804 | 681 | 711 | 469 | 743 | 715 | 651 | 364 |
| Miroc3.2 | Quartile 1 | 767 | 850 | 807 | 793 | 552 | 836 | 760 | 682 | 577 |
| | Median | 816 | 874 | 889 | 843 | 603 | 870 | 776 | 707 | 668 |
| | Quartile 2 | 855 | 885 | 912 | 886 | 643 | 896 | 797 | 729 | 735 |
| | Maximum | 911 | 910 | 930 | 923 | 732 | 920 | 824 | 765 | 812 |
| | Average | 811 | 866 | 858 | 838 | 601 | 864 | 776 | 707 | 654 |
| 2050 MEDRES | Minimum | 718 | 804 | 681 | 710 | 467 | 741 | 712 | 650 | 364 |
| Miroc3.2 | Quartile 1 | 767 | 849 | 806 | 792 | 553 | 832 | 757 | 680 | 576 |
| | Median | 817 | 875 | 889 | 842 | 602 | 867 | 773 | 704 | 668 |
| | Quartile 2 | 856 | 886 | 914 | 884 | 643 | 892 | 794 | 725 | 735 |
| | Maximum | 912 | 913 | 936 | 921 | 731 | 917 | 820 | 761 | 810 |
| | Average | 812 | 867 | 859 | 837 | 601 | 860 | 772 | 704 | 654 |
| 2070 MEDRES | Minimum | 718 | 804 | 681 | 709 | 466 | 740 | 711 | 649 | 363 |
| Miroc3.2 | Quartile 1 | 766 | 850 | 806 | 791 | 551 | 831 | 755 | 678 | 576 |
| | Median | 817 | 875 | 888 | 843 | 601 | 866 | 772 | 703 | 667 |
| | Quartile 2 | 856 | 886 | 915 | 883 | 642 | 891 | 792 | 723 | 734 |
| | Maximum | 911 | 912 | 940 | 922 | 730 | 915 | 818 | 760 | 810 |
| | Average | 811 | 867 | 859 | 836 | 600 | 859 | 771 | 702 | 653 |
| 2030 | Minimum | 724 | 815 | 690 | 721 | 472 | 753 | 724 | 661 | 374 |
| CSIRO Mk3.5 | Quartile 1 | 775 | 861 | 817 | 802 | 556 | 846 | 770 | 692 | 586 |
| | Median | 822 | 882 | 898 | 854 | 607 | 880 | 786 | 717 | 677 |
| | Quartile 2 | 862 | 893 | 921 | 896 | 647 | 906 | 807 | 739 | 745 |
| | Maximum | 921 | 917 | 936 | 934 | 735 | 930 | 834 | 775 | 821 |
| | Average | 818 | 875 | 867 | 848 | 605 | 874 | 786 | 717 | 663 |
| 2050 | Minimum | 755 | 845 | 722 | 748 | 491 | 778 | 750 | 688 | 400 |
| CSIRO Mk3.5 | Quartile 1 | 806 | 891 | 848 | 832 | 576 | 869 | 793 | 717 | 613 |
| | Median | 854 | 914 | 930 | 883 | 626 | 905 | 810 | 742 | 704 |
| | Quartile 2 | 893 | 926 | 952 | 924 | 667 | 930 | 832 | 763 | 771 |
| | Maximum | 952 | 949 | 968 | 964 | 755 | 955 | 857 | 799 | 847 |
| | Average | 849 | 906 | 898 | 877 | 624 | 898 | 810 | 741 | 690 |
| 2070 | Minimum | 735 | 832 | 707 | 738 | 478 | 768 | 739 | 677 | 389 |
| CSIRO Mk3.5 | Quartile 1 | 788 | 878 | 834 | 819 | 563 | 858 | 782 | 707 | 602 |
| | Median | 834 | 896 | 917 | 870 | 613 | 894 | 800 | 731 | 693 |
| | Quartile 2 | 873 | 908 | 939 | 911 | 653 | 919 | 821 | 752 | 760 |
| | Maximum | 939 | 934 | 954 | 950 | 741 | 944 | 846 | 788 | 836 |
| | Average | 831 | 891 | 885 | 865 | 611 | 887 | 799 | 730 | 679 |

†Wine regions: SD = Swan District, PH = Perth Hills, PL = Peel, GR-Geographe, MR = Margaret River, BW = Blackwood Valley, MJ = Manjimup, PM = Pemberton, GS = Great Southern

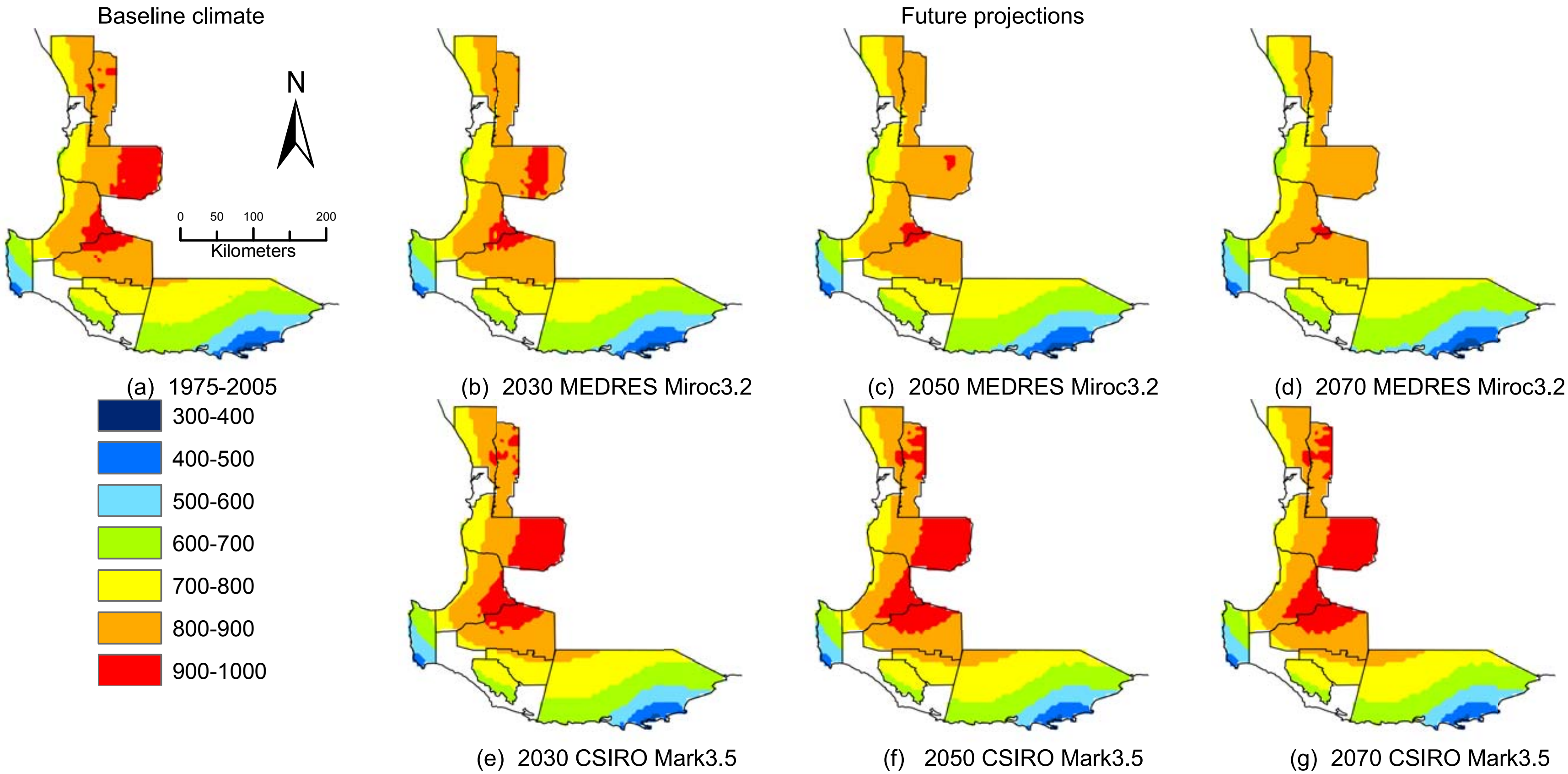


Figure 4.6 Summation of current and projected diurnal range during February to March (°C) under SRES A2 emission scenario

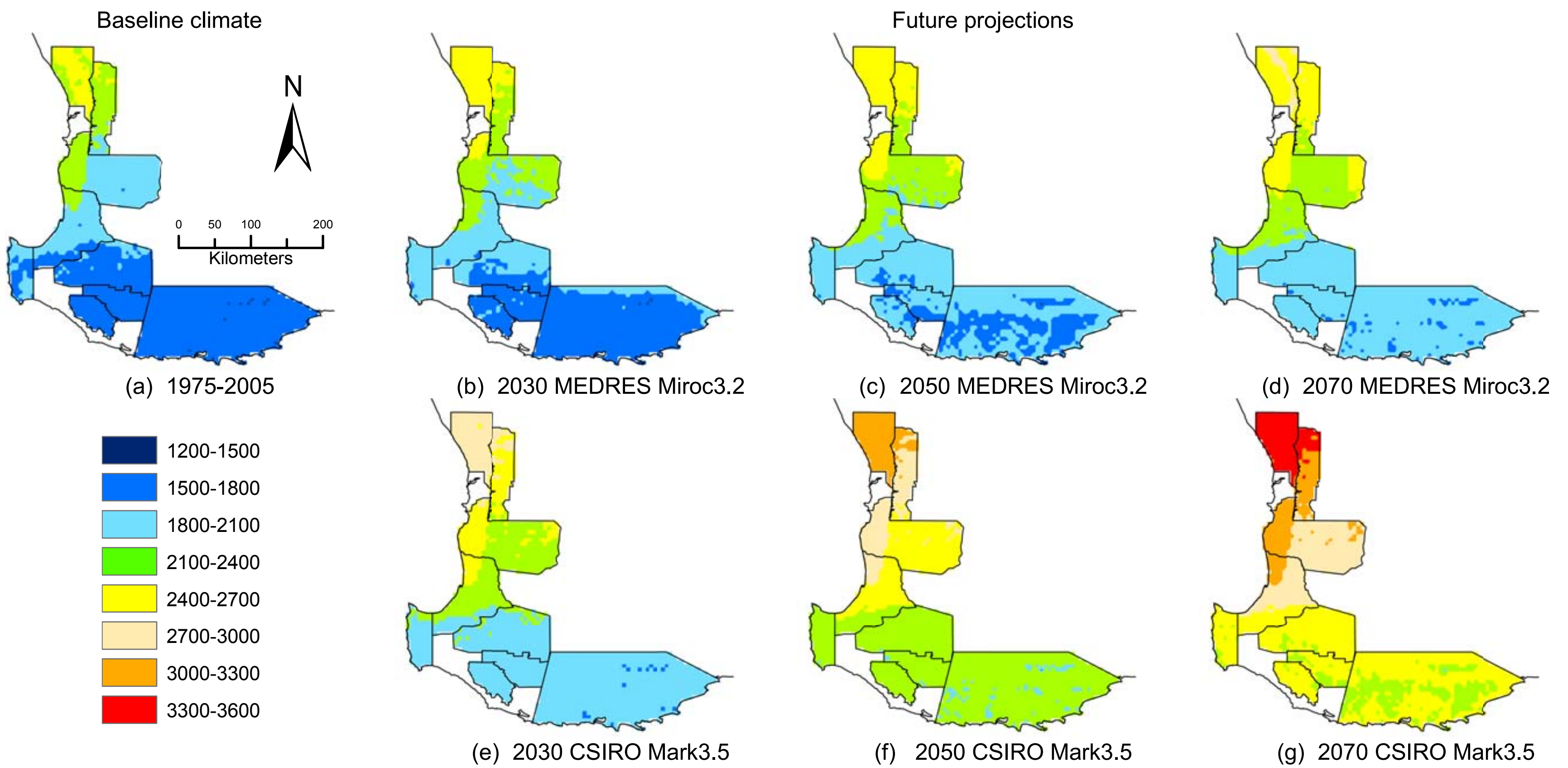


Figure 4.7 Summation of current and projected Growing degree days (°C days) during October to April under SRES A2 emission scenario

The current spatial distribution of GDD patterns is projected shift southward in the future to the extent that by 2070, the GDD currently common for the Swan District will likely prevail in the majority of the Great Southern, Pemberton, Manjimup, Blackwood Valley, Margaret River, and southern parts of the Geographe regions under the highest warming range (Figure 4.7g). The amount of GDD currently available for the majority of areas in the Peel, Geographe, and northern parts of the Margaret River region are projected to be dominant for the Great Southern, Manjimup, Pemberton, Geographe, and southern Margaret River regions by 2070 under low warming range (Figure 4.7d).

### 4.3.8 Changes in biologically effective degree days

Currently, the lowest average BEDD during October to April is at least 1500 units in the southern regions, with the exception of a few places that have as low as 1260 units in the Great Southern region (Figure 4.8a). The Swan District, northern end of the Perth Hills and northwest Peel regions currently have 1800 or more units of BEDD, which is only 100 or less units short of the full potential of BEDD accumulation during the entire growing season (Figure 4.8a). The average BEDD progressively increases under climate change as the average GST increases. By 2070, under the highest warming range, all regions will likely have an average of at least 1850 units of BEDD, while the Swan District and Perth Hills regions would have the maximum potential BEDD that could accumulate during a grape growing season (Table 4.6). Areas currently having the lowest BEDD, including the majority of the Great Southern, Pemberton, Manjimup, and the Blackwood Valley, are projected to have at least an 8% increase reaching about 1700 units, whilst the remaining wine regions are projected to get more than 1700 units of BEDD by 2070 under the low warming (Figure 4.8; Table 4.6).

Table 4.6 Current and projected growing degree days (GDD) and biologically effective degree days (BEDD) during October to April under SRES A2 emission scenario

| Year and Climate model | Statistics | GDD | | | | | | | | | BEDD | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | [†]Wine regions | | | | | | | | | | | | | | | | | |
| | | SD | PH | PL | GR | MR | BW | MJ | PM | GS | SD | PH | PL | GR | MR | BW | MJ | PM | GS |
| 1990 | Minimum | 2326 | 2005 | 1794 | 1650 | 1629 | 1571 | 1551 | 1590 | 1264 | 1813 | 1680 | 1586 | 1528 | 1600 | 1500 | 1507 | 1533 | 1264 |
| | Quartile 1 | 2393 | 2168 | 1962 | 1847 | 1782 | 1683 | 1621 | 1636 | 1610 | 1829 | 1751 | 1660 | 1630 | 1666 | 1560 | 1546 | 1567 | 1560 |
| | Median | 2412 | 2263 | 2022 | 1929 | 1809 | 1750 | 1651 | 1662 | 1641 | 1834 | 1789 | 1681 | 1667 | 1687 | 1592 | 1562 | 1584 | 1583 |
| | Quartile 2 | 2443 | 2339 | 2148 | 2000 | 1840 | 1787 | 1680 | 1676 | 1686 | 1839 | 1809 | 1763 | 1716 | 1704 | 1612 | 1580 | 1603 | 1611 |
| | Maximum | 2488 | 2462 | 2370 | 2178 | 1953 | 1870 | 1728 | 1766 | 1810 | 1846 | 1830 | 1834 | 1799 | 1750 | 1659 | 1609 | 1645 | 1695 |
| | Average | 2418 | 2249 | 2057 | 1929 | 1818 | 1739 | 1650 | 1662 | 1642 | 1833 | 1778 | 1707 | 1674 | 1685 | 1586 | 1562 | 1586 | 1580 |
| 2030 | Minimum | 2430 | 2113 | 1902 | 1740 | 1711 | 1659 | 1637 | 1676 | 1358 | 1827 | 1718 | 1624 | 1585 | 1653 | 1567 | 1573 | 1594 | 1358 |
| MEDRES | Quartile 1 | 2495 | 2273 | 2073 | 1938 | 1867 | 1775 | 1707 | 1721 | 1700 | 1842 | 1789 | 1701 | 1668 | 1717 | 1613 | 1606 | 1623 | 1622 |
| Miroc3.2 | Median | 2514 | 2368 | 2139 | 2021 | 1892 | 1840 | 1739 | 1746 | 1730 | 1847 | 1813 | 1726 | 1700 | 1732 | 1632 | 1620 | 1640 | 1642 |
| | Quartile 2 | 2546 | 2446 | 2264 | 2101 | 1924 | 1877 | 1769 | 1760 | 1777 | 1852 | 1823 | 1801 | 1749 | 1747 | 1647 | 1637 | 1658 | 1665 |
| | Maximum | 2593 | 2567 | 2472 | 2280 | 2037 | 1967 | 1816 | 1851 | 1898 | 1859 | 1843 | 1847 | 1825 | 1780 | 1697 | 1662 | 1698 | 1734 |
| | Average | 2520 | 2356 | 2173 | 2025 | 1901 | 1829 | 1737 | 1747 | 1732 | 1846 | 1803 | 1744 | 1711 | 1730 | 1631 | 1620 | 1642 | 1639 |
| 2050 | Minimum | 2522 | 2205 | 1994 | 1814 | 1786 | 1734 | 1712 | 1751 | 1440 | 1841 | 1759 | 1665 | 1618 | 1697 | 1608 | 1616 | 1637 | 1427 |
| MEDRES | Quartile 1 | 2586 | 2365 | 2170 | 2012 | 1941 | 1850 | 1783 | 1796 | 1782 | 1856 | 1815 | 1742 | 1703 | 1750 | 1646 | 1647 | 1667 | 1667 |
| Miroc3.2 | Median | 2606 | 2460 | 2235 | 2102 | 1967 | 1915 | 1814 | 1821 | 1813 | 1861 | 1827 | 1770 | 1738 | 1765 | 1665 | 1658 | 1683 | 1683 |
| | Quartile 2 | 2637 | 2537 | 2401 | 2193 | 1999 | 1954 | 1845 | 1836 | 1859 | 1867 | 1837 | 1826 | 1785 | 1778 | 1679 | 1672 | 1697 | 1704 |
| | Maximum | 2685 | 2659 | 2563 | 2372 | 2112 | 2049 | 1891 | 1926 | 1981 | 1874 | 1857 | 1861 | 1839 | 1806 | 1730 | 1695 | 1731 | 1770 |
| | Average | 2612 | 2447 | 2274 | 2108 | 1976 | 1905 | 1813 | 1823 | 1814 | 1861 | 1824 | 1780 | 1745 | 1763 | 1664 | 1658 | 1683 | 1683 |
| 2070 | Minimum | 2583 | 2266 | 2055 | 1865 | 1837 | 1785 | 1763 | 1802 | 1496 | 1851 | 1787 | 1693 | 1640 | 1726 | 1630 | 1645 | 1664 | 1467 |
| MEDRES | Quartile 1 | 2648 | 2427 | 2232 | 2068 | 1992 | 1901 | 1833 | 1847 | 1837 | 1866 | 1825 | 1769 | 1727 | 1772 | 1668 | 1670 | 1692 | 1692 |
| Miroc3.2 | Median | 2668 | 2521 | 2298 | 2158 | 2017 | 1965 | 1865 | 1872 | 1868 | 1871 | 1837 | 1791 | 1764 | 1787 | 1687 | 1681 | 1706 | 1708 |
| | Quartile 2 | 2699 | 2599 | 2477 | 2254 | 2049 | 2005 | 1895 | 1886 | 1915 | 1876 | 1847 | 1841 | 1808 | 1796 | 1702 | 1694 | 1720 | 1731 |
| | Maximum | 2746 | 2720 | 2625 | 2434 | 2162 | 2104 | 1942 | 1977 | 2036 | 1883 | 1867 | 1871 | 1849 | 1821 | 1752 | 1717 | 1753 | 1792 |
| | Average | 2673 | 2509 | 2343 | 2164 | 2026 | 1955 | 1864 | 1873 | 1870 | 1870 | 1836 | 1802 | 1766 | 1783 | 1686 | 1681 | 1707 | 1710 |
| 2030 | Minimum | 2695 | 2352 | 2141 | 1940 | 1861 | 1859 | 1837 | 1876 | 1554 | 1856 | 1807 | 1719 | 1670 | 1738 | 1660 | 1675 | 1693 | 1514 |
| CSIRO | Quartile 1 | 2752 | 2513 | 2308 | 2157 | 2017 | 1973 | 1907 | 1921 | 1896 | 1871 | 1829 | 1791 | 1757 | 1779 | 1698 | 1699 | 1721 | 1718 |
| Mk3.5 | Median | 2775 | 2615 | 2369 | 2254 | 2042 | 2040 | 1939 | 1946 | 1926 | 1876 | 1841 | 1805 | 1794 | 1791 | 1717 | 1710 | 1736 | 1735 |
| | Quartile 2 | 2807 | 2710 | 2492 | 2343 | 2074 | 2077 | 1967 | 1960 | 1973 | 1881 | 1852 | 1840 | 1827 | 1799 | 1731 | 1723 | 1749 | 1755 |
| | Maximum | 2858 | 2832 | 2710 | 2519 | 2207 | 2160 | 2016 | 2051 | 2095 | 1889 | 1873 | 1875 | 1853 | 1829 | 1782 | 1747 | 1780 | 1805 |
| | Average | 2779 | 2604 | 2402 | 2252 | 2051 | 2028 | 1937 | 1947 | 1928 | 1876 | 1841 | 1812 | 1790 | 1788 | 1716 | 1711 | 1736 | 1734 |
| 2050 | Minimum | 2991 | 2635 | 2423 | 2175 | 2053 | 2095 | 2073 | 2111 | 1793 | 1893 | 1843 | 1810 | 1771 | 1797 | 1760 | 1773 | 1786 | 1660 |
| CSIRO | Quartile 1 | 3055 | 2795 | 2591 | 2400 | 2209 | 2208 | 2143 | 2157 | 2135 | 1908 | 1865 | 1835 | 1832 | 1832 | 1792 | 1788 | 1801 | 1794 |
| Mk3.5 | Median | 3080 | 2898 | 2651 | 2529 | 2234 | 2275 | 2175 | 2182 | 2164 | 1908 | 1878 | 1842 | 1842 | 1841 | 1809 | 1794 | 1810 | 1808 |
| | Quartile 2 | 3108 | 3008 | 2774 | 2625 | 2266 | 2312 | 2203 | 2196 | 2212 | 1908 | 1890 | 1876 | 1862 | 1847 | 1816 | 1803 | 1818 | 1823 |
| | Maximum | 3164 | 3138 | 2993 | 2802 | 2420 | 2395 | 2252 | 2287 | 2334 | 1908 | 1908 | 1908 | 1889 | 1862 | 1842 | 1818 | 1843 | 1854 |
| | Average | 3080 | 2895 | 2685 | 2517 | 2243 | 2264 | 2173 | 2183 | 2166 | 1907 | 1878 | 1854 | 1845 | 1839 | 1805 | 1795 | 1811 | 1807 |
| 2070 | Minimum | 3294 | 2938 | 2726 | 2427 | 2259 | 2347 | 2325 | 2364 | 2049 | 1908 | 1882 | 1849 | 1834 | 1852 | 1831 | 1834 | 1844 | 1758 |
| CSIRO | Quartile 1 | 3378 | 3098 | 2893 | 2652 | 2414 | 2461 | 2396 | 2409 | 2390 | 1908 | 1904 | 1874 | 1867 | 1865 | 1840 | 1843 | 1853 | 1846 |
| Mk3.5 | Median | 3405 | 3201 | 2954 | 2832 | 2439 | 2527 | 2427 | 2435 | 2419 | 1908 | 1908 | 1881 | 1879 | 1871 | 1845 | 1845 | 1859 | 1854 |
| | Quartile 2 | 3434 | 3325 | 3077 | 2928 | 2471 | 2564 | 2455 | 2449 | 2467 | 1908 | 1908 | 1908 | 1901 | 1876 | 1850 | 1849 | 1864 | 1864 |
| | Maximum | 3492 | 3466 | 3296 | 3104 | 2649 | 2647 | 2504 | 2540 | 2590 | 1908 | 1908 | 1908 | 1908 | 1893 | 1876 | 1861 | 1877 | 1890 |
| | Average | 3403 | 3207 | 2988 | 2801 | 2449 | 2516 | 2425 | 2436 | 2421 | 1908 | 1905 | 1885 | 1881 | 1870 | 1846 | 1846 | 1859 | 1854 |

[†]Wine regions: SD = Swan District, PH = Perth Hills, PL = Peel, GR-Geographe, MR = Margaret River, BW = Blackwood Valley, MJ = Manjimup, PM = Pemberton, GS = Great Southern

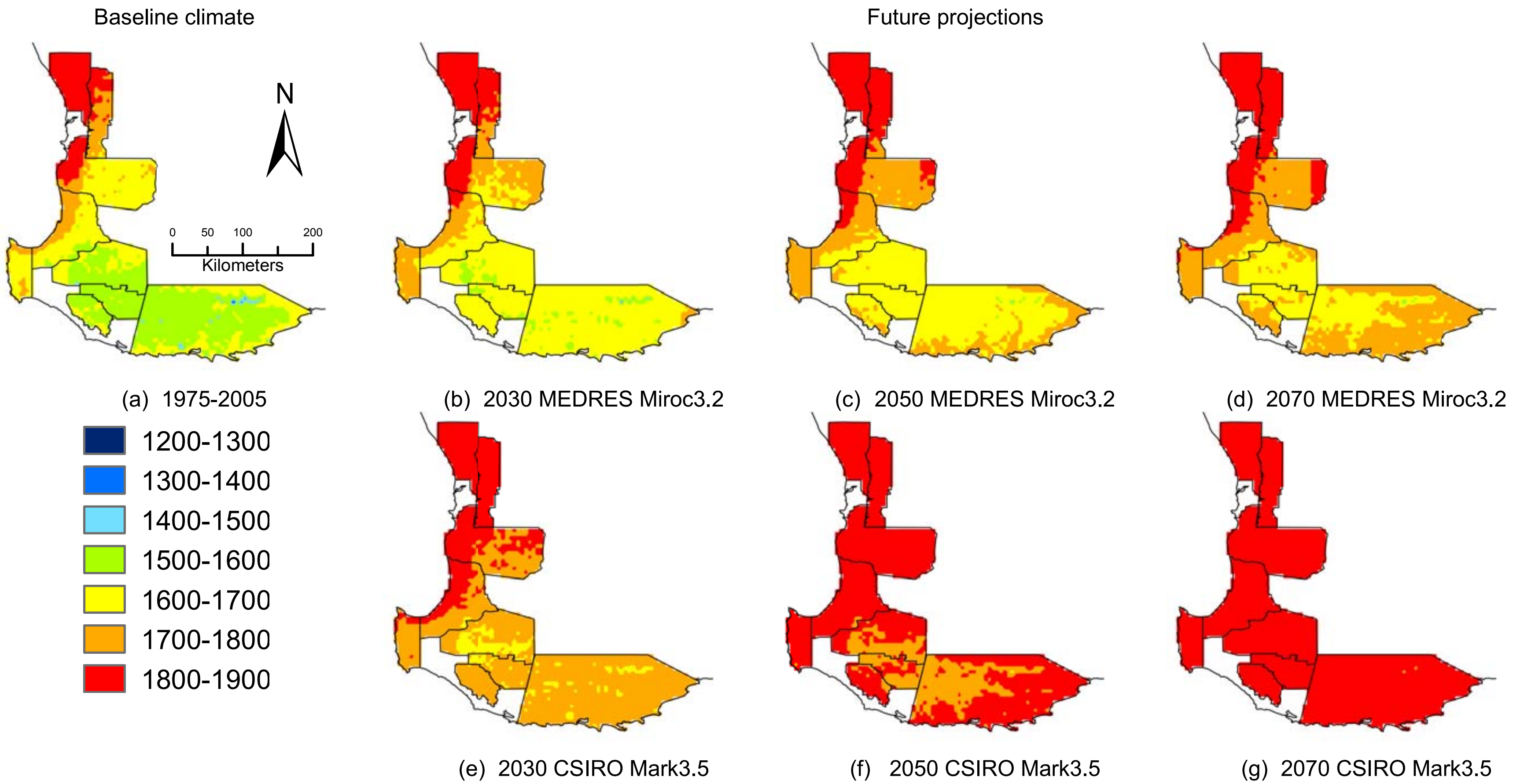


Figure 4.8 Summation of current and projected Biologically effective growing degree days during October to April under SRES A2 emission scenario

### 4.3.9 Frequency of hot days during the grape growing season

Currently, the frequency of the average number of days with a daily maximum temperature ($T_{max}$) over 25°C ranges from 146 in the Swan District to 67 in the Great Southern wine region. When $T_{max}$ is over 30°C then the range is 73 for the Swan District to 22 for the Great Southern region. The only exception to this north to south decreasing trend is for the Margaret River region, which experiences less variation and currently has an average of 68 and 13 days respectively when the maximum temperatures are over 25°C and 30°C.

The frequency of these days is projected to increase gradually under climate change. Averaged across the regions, the current number of days exceeding 25°C are projected to increase by 22, 41, and 59 days (and 16, 31, and 48 days for $T_{max}$>30°C), respectively by 2030, 2050, and 2070, under high warming range (Table 4.7; Figure 4.9). Examined individually, these increases vary from region to region: days with $T_{max}$ >25°C will likely double in the Margaret River, Pemberton, and Great Southern regions by 2070 (Table 4.7). This increase is even more dramatic when the $T_{max}$ >30°C is examined: a 2- to 3-fold increase may be experienced in the above regions. However, the total number of hot days are likely to remain lower than the warmer northern wine regions (Table 4.7; Figure 4.9; Figure 4.10).

The changes in the pattern in frequency of hot days under the low warming climate change were similar to the projections under the high warming scenario, however, the magnitudes were projected to be about 5 times less for days with $T_{max}$ >25°C and 3 times less for days with $T_{max}$ >30°C across the future time periods examined in this study.

Table 4.7 Current and projected frequency of hot days during October to April under SRES A2 emission scenario

| Year and Climate model | Statistics | Days with maximum temperature >25°C | | | | | | | | | Days with maximum temperature >30°C | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | [†]Wine regions | | | | | | | | | | | | | | | | | |
| | | **SD** | **PH** | **PL** | **GR** | **MR** | **BW** | **MJ** | **PM** | **GS** | **SD** | **PH** | **PL** | **GR** | **MR** | **BW** | **MJ** | **PM** | **GS** |
| 1990 | Minimum | 130 | 121 | 110 | 86 | 30 | 80 | 68 | 63 | 30 | 57 | 54 | 46 | 22 | 4 | 26 | 22 | 18 | 8 |
| | Quartile 1 | 141 | 133 | 124 | 112 | 59 | 95 | 79 | 69 | 54 | 65 | 64 | 56 | 43 | 8 | 37 | 28 | 21 | 15 |
| | Median | 147 | 143 | 129 | 117 | 69 | 105 | 85 | 73 | 67 | 73 | 74 | 61 | 50 | 12 | 43 | 31 | 22 | 21 |
| | Quartile 2 | 152 | 150 | 134 | 121 | 77 | 112 | 87 | 76 | 80 | 80 | 82 | 66 | 53 | 17 | 49 | 33 | 25 | 28 |
| | Maximum | 160 | 159 | 143 | 128 | 102 | 122 | 95 | 86 | 98 | 90 | 91 | 76 | 60 | 31 | 55 | 39 | 30 | 40 |
| | Average | 146 | 141 | 129 | 116 | 68 | 104 | 83 | 73 | 67 | 73 | 73 | 61 | 48 | 13 | 43 | 31 | 23 | 22 |
| 2030 MEDRES Miroc3.2 | Minimum | 136 | 126 | 116 | 91 | 35 | 84 | 72 | 67 | 33 | 61 | 58 | 49 | 24 | 4 | 29 | 24 | 19 | 9 |
| | Quartile 1 | 147 | 138 | 129 | 117 | 65 | 100 | 83 | 74 | 59 | 70 | 68 | 60 | 47 | 9 | 40 | 30 | 23 | 17 |
| | Median | 153 | 148 | 134 | 123 | 75 | 110 | 89 | 77 | 72 | 78 | 79 | 65 | 53 | 14 | 46 | 34 | 24 | 23 |
| | Quartile 2 | 157 | 154 | 139 | 126 | 82 | 117 | 92 | 81 | 86 | 85 | 87 | 71 | 57 | 19 | 52 | 36 | 27 | 31 |
| | Maximum | 164 | 163 | 149 | 133 | 107 | 126 | 100 | 90 | 104 | 95 | 96 | 82 | 64 | 34 | 59 | 41 | 32 | 44 |
| | Average | 152 | 146 | 134 | 121 | 74 | 109 | 88 | 77 | 73 | 78 | 77 | 65 | 51 | 15 | 46 | 33 | 25 | 24 |
| 2050 MEDRES Miroc3.2 | Minimum | 141 | 130 | 120 | 96 | 40 | 89 | 76 | 72 | 35 | 64 | 61 | 53 | 26 | 5 | 31 | 26 | 21 | 10 |
| | Quartile 1 | 152 | 142 | 133 | 121 | 71 | 105 | 88 | 78 | 63 | 74 | 72 | 64 | 50 | 11 | 43 | 32 | 25 | 19 |
| | Median | 157 | 152 | 139 | 127 | 81 | 115 | 93 | 81 | 77 | 83 | 83 | 69 | 57 | 16 | 49 | 36 | 26 | 25 |
| | Quartile 2 | 161 | 159 | 144 | 131 | 89 | 121 | 96 | 85 | 90 | 89 | 90 | 75 | 61 | 22 | 55 | 38 | 29 | 34 |
| | Maximum | 169 | 167 | 156 | 137 | 113 | 130 | 104 | 95 | 109 | 100 | 100 | 89 | 67 | 37 | 62 | 44 | 35 | 46 |
| | Average | 156 | 150 | 139 | 125 | 80 | 113 | 92 | 82 | 77 | 82 | 81 | 70 | 54 | 17 | 49 | 35 | 27 | 26 |
| 2070 MEDRES Miroc3.2 | Minimum | 145 | 134 | 122 | 100 | 43 | 92 | 79 | 75 | 37 | 67 | 64 | 55 | 28 | 5 | 33 | 27 | 22 | 10 |
| | Quartile 1 | 155 | 145 | 137 | 125 | 75 | 107 | 90 | 81 | 66 | 77 | 74 | 66 | 52 | 12 | 45 | 34 | 26 | 20 |
| | Median | 160 | 155 | 142 | 131 | 85 | 118 | 96 | 84 | 80 | 86 | 86 | 72 | 59 | 17 | 51 | 38 | 28 | 26 |
| | Quartile 2 | 164 | 161 | 147 | 135 | 93 | 124 | 99 | 88 | 94 | 92 | 94 | 78 | 63 | 23 | 57 | 40 | 31 | 35 |
| | Maximum | 171 | 170 | 161 | 140 | 117 | 133 | 107 | 99 | 112 | 103 | 103 | 93 | 71 | 39 | 65 | 45 | 36 | 48 |
| | Average | 160 | 153 | 142 | 129 | 84 | 116 | 95 | 85 | 80 | 85 | 84 | 72 | 57 | 18 | 51 | 37 | 28 | 27 |
| 2030 CSIRO Mk3.5 | Minimum | 158 | 145 | 134 | 112 | 48 | 101 | 87 | 85 | 42 | 79 | 75 | 65 | 34 | 6 | 39 | 31 | 26 | 12 |
| | Quartile 1 | 168 | 155 | 148 | 136 | 83 | 118 | 100 | 90 | 74 | 90 | 86 | 78 | 61 | 14 | 50 | 39 | 30 | 23 |
| | Median | 171 | 163 | 152 | 142 | 92 | 127 | 105 | 94 | 88 | 99 | 97 | 83 | 69 | 20 | 57 | 42 | 32 | 30 |
| | Quartile 2 | 175 | 171 | 156 | 145 | 99 | 133 | 108 | 98 | 103 | 105 | 106 | 88 | 74 | 26 | 64 | 45 | 36 | 39 |
| | Maximum | 180 | 179 | 166 | 152 | 123 | 141 | 117 | 109 | 119 | 117 | 116 | 98 | 82 | 43 | 72 | 51 | 41 | 53 |
| | Average | 171 | 163 | 152 | 140 | 91 | 126 | 104 | 94 | 88 | 98 | 96 | 82 | 66 | 20 | 57 | 42 | 33 | 31 |
| 2050 CSIRO Mk3.5 | Minimum | 178 | 164 | 154 | 134 | 68 | 122 | 105 | 105 | 57 | 101 | 95 | 85 | 47 | 8 | 49 | 41 | 36 | 17 |
| | Quartile 1 | 185 | 172 | 165 | 153 | 104 | 135 | 118 | 110 | 96 | 113 | 105 | 98 | 76 | 21 | 63 | 49 | 41 | 31 |
| | Median | 187 | 179 | 170 | 161 | 112 | 144 | 125 | 114 | 109 | 122 | 118 | 103 | 90 | 28 | 71 | 54 | 43 | 40 |
| | Quartile 2 | 189 | 185 | 173 | 165 | 118 | 149 | 128 | 118 | 123 | 128 | 128 | 108 | 94 | 34 | 78 | 57 | 46 | 51 |
| | Maximum | 192 | 191 | 183 | 171 | 141 | 157 | 135 | 131 | 138 | 138 | 137 | 118 | 101 | 54 | 86 | 65 | 53 | 66 |
| | Average | 187 | 179 | 169 | 159 | 111 | 142 | 123 | 114 | 109 | 120 | 117 | 103 | 85 | 28 | 71 | 53 | 43 | 41 |
| 2070 CSIRO Mk3.5 | Minimum | 193 | 180 | 171 | 155 | 95 | 142 | 129 | 132 | 79 | 125 | 116 | 106 | 66 | 13 | 66 | 53 | 49 | 23 |
| | Quartile 1 | 197 | 187 | 181 | 172 | 128 | 155 | 141 | 135 | 121 | 139 | 128 | 119 | 96 | 30 | 79 | 65 | 55 | 42 |
| | Median | 198 | 192 | 184 | 179 | 134 | 162 | 146 | 139 | 134 | 145 | 139 | 125 | 112 | 39 | 88 | 71 | 58 | 53 |
| | Quartile 2 | 200 | 196 | 188 | 182 | 140 | 167 | 148 | 142 | 146 | 150 | 147 | 130 | 117 | 46 | 96 | 73 | 61 | 65 |
| | Maximum | 201 | 201 | 195 | 186 | 159 | 174 | 155 | 153 | 158 | 158 | 156 | 138 | 124 | 69 | 106 | 80 | 70 | 82 |
| | Average | 198 | 191 | 184 | 177 | 134 | 161 | 144 | 139 | 133 | 144 | 138 | 124 | 106 | 39 | 88 | 69 | 58 | 54 |

[†]Wine regions: SD = Swan District, PH = Perth Hills, PL = Peel, GR-Geographe, MR = Margaret River, BW = Blackwood Valley, MJ = Manjimup, PM = Pemberton, GS = Great Southern

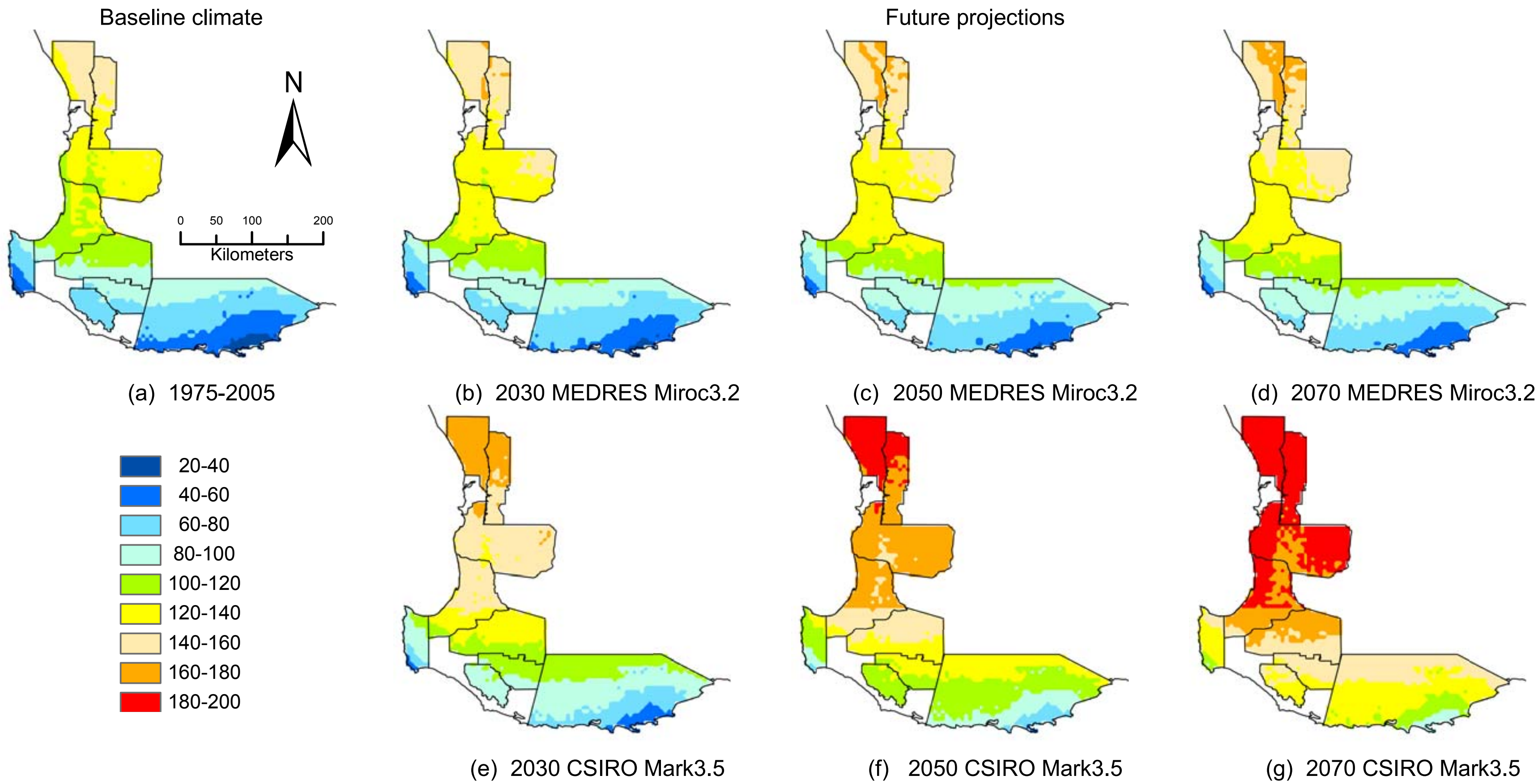


Figure 4.9 Current and projected number of days with maximum temperature over 25°C during October to April under SRES A2 emission scenario

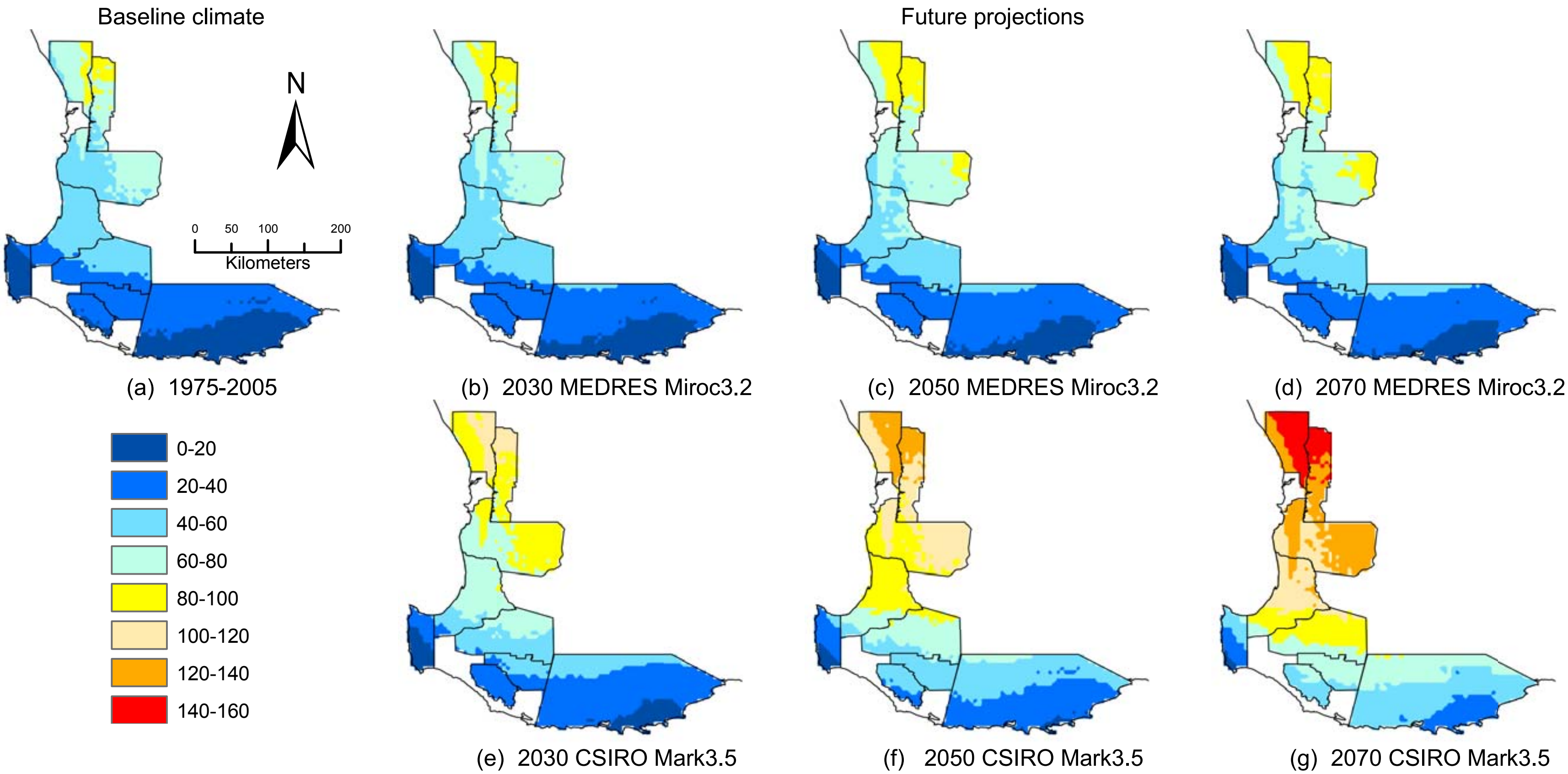


Figure 4.10 Current and projected number of days with maximum temperature over 30°C during October to April under SRES A2 emission scenario

### 4.3.10 Changes in seasonal distribution of rainfall

Currently, wine regions or parts of a region close to the southwest corner of the state receive higher rainfall than areas further inland. For example, the Margaret River, Pemberton, and southwest corner of the Great Southern regions receive 900 to1400 mm annual rainfall, while the inland northeast corner of the Great Southern gets about one third of this amount (Figure 4.11). This spatial pattern is generally repeated for future rainfall distributions under climate change, but with a progressive decline in the amount of rainfall and the magnitude of the change varying between the seasons (Table 4.8 to 4.10; Figure 4.11 to 4.16).

Projected under low and high warming, annual rainfall is projected to decline on average by 5 to 8% by 2030, 11 to 16% by 2050, and 15 to 24% by 2070 across WA wine regions and the decline will likely differ between seasons. For example, averaged for a region, the greatest decreases were projected for spring rainfall with as much as a 76% decline in the Swan District followed by the Perth Hills (72%), and the Great Southern (65%) regions under high warming climate change range by 2070 (Table 4.9; Figure 4.13). This decline in spring rainfall apparently causes the grape growing season rainfall to drop 22 to 45% across the wine regions (Table 4.8; Figure 4.12) as most of the growing season rainfall occurs during the spring months in the study regions. On the other hand, the least decline in future rainfall is for the autumn season with the highest decline of 20% for the Margaret River region, and the lowest of 3% for the Great Southern region (Table 4.10; Figure 4.15).

Similarly, under the lowest warming range, the spring rainfall decline remained the highest of all the seasons. Nevertheless, regions that would experience the most decline and the magnitudes of these decreases were different. For example, by 2070 the reduction in average spring rainfall is projected to be as much as 24% for the Peel region, while the others are projected to have 19 to 20% reduction (Table 4.9).

Table 4.8 Current and projected annual and October to April period rainfall under SRES A2 emission scenario

| Year and Climate model | Statistics | Annual Rainfall (mm) | | | | | | | | | Growing Season rainfall (mm) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | †Wine regions | | | | | | | | | | | | | | | | | |
| | | SD | PH | PL | GR | MR | BW | MJ | PM | GS | SD | PH | PL | GR | MR | BW | MJ | PM | GS |
| 1990 | Minimum | 574 | 601 | 458 | 736 | 837 | 510 | 645 | 973 | 383 | 129 | 138 | 134 | 166 | 171 | 151 | 194 | 272 | 151 |
| | Quartile 1 | 678 | 716 | 598 | 862 | 1004 | 612 | 774 | 1094 | 523 | 145 | 161 | 163 | 192 | 213 | 179 | 229 | 298 | 205 |
| | Median | 726 | 850 | 840 | 908 | 1044 | 713 | 852 | 1148 | 673 | 154 | 185 | 190 | 206 | 237 | 200 | 246 | 307 | 251 |
| | Quartile 2 | 784 | 1000 | 936 | 954 | 1107 | 887 | 944 | 1171 | 914 | 163 | 225 | 213 | 220 | 244 | 223 | 266 | 317 | 306 |
| | Maximum | 849 | 1113 | 1210 | 1170 | 1157 | 1040 | 1059 | 1212 | 1346 | 180 | 257 | 270 | 262 | 260 | 271 | 303 | 325 | 392 |
| | Average | 729 | 860 | 791 | 913 | 1037 | 748 | 850 | 1133 | 703 | 153 | 193 | 192 | 206 | 228 | 202 | 246 | 305 | 251 |
| 2030 | Minimum | 545 | 570 | 433 | 693 | 780 | 483 | 611 | 920 | 366 | 127 | 135 | 131 | 159 | 162 | 146 | 187 | 261 | 146 |
| MEDRES | Quartile 1 | 643 | 678 | 564 | 812 | 941 | 579 | 733 | 1034 | 500 | 142 | 157 | 158 | 185 | 201 | 172 | 220 | 286 | 198 |
| Miroc3.2 | Median | 687 | 798 | 791 | 856 | 979 | 675 | 806 | 1084 | 643 | 151 | 178 | 183 | 199 | 224 | 192 | 236 | 294 | 242 |
| | Quartile 2 | 741 | 940 | 880 | 899 | 1038 | 839 | 893 | 1107 | 869 | 159 | 217 | 205 | 211 | 230 | 214 | 255 | 304 | 295 |
| | Maximum | 798 | 1046 | 1137 | 1099 | 1085 | 982 | 1001 | 1145 | 1274 | 174 | 247 | 260 | 251 | 246 | 260 | 291 | 312 | 378 |
| | Average | 689 | 810 | 745 | 860 | 973 | 708 | 804 | 1071 | 670 | 149 | 186 | 185 | 198 | 215 | 194 | 236 | 293 | 242 |
| 2050 | Minimum | 513 | 536 | 405 | 647 | 719 | 454 | 574 | 863 | 349 | 124 | 132 | 127 | 152 | 152 | 140 | 178 | 248 | 140 |
| MEDRES | Quartile 1 | 604 | 637 | 527 | 759 | 873 | 544 | 688 | 968 | 475 | 138 | 153 | 152 | 177 | 189 | 165 | 210 | 272 | 191 |
| Miroc3.2 | Median | 645 | 743 | 737 | 799 | 909 | 634 | 756 | 1016 | 610 | 147 | 172 | 175 | 189 | 210 | 184 | 225 | 280 | 233 |
| | Quartile 2 | 694 | 874 | 819 | 841 | 963 | 786 | 837 | 1037 | 820 | 154 | 208 | 197 | 202 | 216 | 204 | 243 | 290 | 284 |
| | Maximum | 742 | 973 | 1058 | 1022 | 1007 | 920 | 938 | 1074 | 1195 | 167 | 236 | 249 | 240 | 231 | 247 | 277 | 297 | 364 |
| | Average | 646 | 756 | 695 | 803 | 903 | 664 | 754 | 1003 | 634 | 145 | 180 | 178 | 190 | 201 | 186 | 226 | 279 | 233 |
| 2070 | Minimum | 492 | 513 | 387 | 616 | 678 | 434 | 549 | 824 | 337 | 122 | 130 | 124 | 147 | 145 | 136 | 173 | 240 | 136 |
| MEDRES | Quartile 1 | 578 | 609 | 502 | 722 | 827 | 521 | 658 | 924 | 457 | 136 | 151 | 149 | 172 | 180 | 160 | 204 | 263 | 186 |
| Miroc3.2 | Median | 617 | 708 | 701 | 762 | 862 | 606 | 722 | 970 | 588 | 144 | 167 | 170 | 183 | 201 | 178 | 218 | 271 | 226 |
| | Quartile 2 | 662 | 830 | 779 | 799 | 913 | 751 | 800 | 991 | 788 | 150 | 201 | 191 | 195 | 206 | 198 | 235 | 281 | 275 |
| | Maximum | 705 | 924 | 1005 | 970 | 954 | 878 | 895 | 1025 | 1142 | 163 | 229 | 241 | 233 | 220 | 239 | 269 | 287 | 354 |
| | Average | 617 | 719 | 661 | 764 | 855 | 635 | 721 | 958 | 610 | 142 | 175 | 173 | 184 | 192 | 180 | 219 | 270 | 227 |
| 2030 | Minimum | 526 | 537 | 447 | 703 | 799 | 488 | 617 | 903 | 368 | 113 | 118 | 129 | 161 | 171 | 150 | 199 | 249 | 150 |
| CSIRO | Quartile 1 | 610 | 641 | 573 | 805 | 946 | 578 | 727 | 989 | 475 | 121 | 133 | 152 | 179 | 208 | 174 | 219 | 266 | 185 |
| Mk3.5 | Median | 654 | 767 | 803 | 835 | 987 | 681 | 797 | 1033 | 610 | 128 | 154 | 178 | 188 | 231 | 191 | 232 | 276 | 224 |
| | Quartile 2 | 715 | 899 | 874 | 881 | 1028 | 804 | 870 | 1057 | 831 | 137 | 184 | 197 | 195 | 236 | 203 | 246 | 282 | 276 |
| | Maximum | 789 | 1007 | 1048 | 1030 | 1069 | 943 | 947 | 1087 | 1230 | 163 | 221 | 224 | 219 | 243 | 236 | 274 | 298 | 354 |
| | Average | 661 | 770 | 744 | 845 | 977 | 694 | 792 | 1022 | 640 | 130 | 159 | 176 | 188 | 222 | 189 | 232 | 274 | 227 |
| 2050 | Minimum | 476 | 487 | 413 | 649 | 736 | 443 | 560 | 819 | 325 | 92 | 97 | 113 | 141 | 155 | 133 | 176 | 221 | 128 |
| CSIRO | Quartile 1 | 554 | 582 | 530 | 741 | 869 | 524 | 660 | 898 | 422 | 99 | 109 | 133 | 157 | 188 | 154 | 194 | 235 | 160 |
| Mk3.5 | Median | 593 | 711 | 746 | 769 | 905 | 618 | 723 | 939 | 547 | 105 | 134 | 155 | 165 | 209 | 169 | 205 | 244 | 195 |
| | Quartile 2 | 655 | 834 | 809 | 809 | 943 | 731 | 790 | 961 | 745 | 114 | 160 | 171 | 171 | 214 | 180 | 218 | 250 | 241 |
| | Maximum | 734 | 934 | 976 | 959 | 981 | 858 | 861 | 989 | 1119 | 142 | 192 | 194 | 197 | 220 | 209 | 243 | 265 | 315 |
| | Average | 604 | 710 | 690 | 780 | 896 | 630 | 719 | 928 | 572 | 108 | 136 | 154 | 164 | 201 | 168 | 206 | 243 | 198 |
| 2070 | Minimum | 423 | 433 | 377 | 592 | 668 | 395 | 498 | 729 | 279 | 71 | 75 | 97 | 119 | 137 | 115 | 153 | 190 | 105 |
| CSIRO | Quartile 1 | 494 | 518 | 485 | 669 | 783 | 468 | 588 | 801 | 366 | 76 | 85 | 112 | 133 | 168 | 134 | 168 | 203 | 134 |
| Mk3.5 | Median | 529 | 653 | 684 | 700 | 817 | 552 | 643 | 838 | 476 | 80 | 111 | 131 | 139 | 186 | 146 | 177 | 210 | 163 |
| | Quartile 2 | 591 | 765 | 742 | 739 | 853 | 653 | 703 | 858 | 654 | 90 | 135 | 144 | 146 | 191 | 155 | 188 | 216 | 205 |
| | Maximum | 674 | 857 | 899 | 883 | 887 | 768 | 769 | 884 | 999 | 119 | 160 | 162 | 174 | 196 | 180 | 210 | 229 | 273 |
| | Average | 543 | 647 | 631 | 709 | 809 | 563 | 640 | 829 | 500 | 85 | 111 | 129 | 140 | 178 | 145 | 178 | 210 | 166 |

†Wine regions: SD = Swan District, PH = Perth Hills, PL = Peel, GR-Geographe, MR = Margaret River, BW = Blackwood Valley, MJ = Manjimup, PM = Pemberton, GS = Great Southern

Another main difference between high warming and low warming climate change ranges is their difference in projecting winter and summer rainfall. In high warming model, the greatest declines in winter rainfall are projected in southern regions, while the low warming model projects the greatest declines to occur in the northern regions (Table 4.10; Figure 4.16). The amount of summer rainfall is presently small, with a high of 61 mm in the Great Southern and a low of 32 mm in the Swan District region (Table 4.9).

Table 4.9 Current and projected Spring (September to November) and Summer (December to January) rainfall under SRES A2 emission scenario

| Year and Climate model | Statistics | Spring Rainfall (mm) †Wine regions | | | | | | | | | Summer Rainfall (mm) †Wine regions | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | SD | PH | PL | GR | MR | BW | MJ | PM | GS | SD | PH | PL | GR | MR | BW | MJ | PM | GS |
| 1990 | Minimum | 108 | 117 | 91 | 160 | 170 | 114 | 156 | 244 | 98 | 32 | 38 | 40 | 34 | 33 | 45 | 52 | 61 | 52 |
| | Quartile 1 | 130 | 148 | 124 | 182 | 214 | 141 | 190 | 270 | 136 | 37 | 42 | 45 | 41 | 42 | 50 | 57 | 68 | 63 |
| | Median | 143 | 176 | 170 | 196 | 227 | 164 | 210 | 277 | 175 | 39 | 45 | 47 | 45 | 49 | 52 | 61 | 70 | 74 |
| | Quartile 2 | 152 | 212 | 194 | 208 | 241 | 203 | 233 | 284 | 231 | 40 | 52 | 52 | 50 | 51 | 54 | 65 | 73 | 81 |
| | Maximum | 169 | 242 | 263 | 254 | 259 | 249 | 261 | 292 | 319 | 45 | 59 | 62 | 57 | 57 | 62 | 75 | 76 | 98 |
| | Average | 141 | 180 | 166 | 196 | 224 | 172 | 210 | 276 | 179 | 38 | 47 | 48 | 46 | 47 | 52 | 62 | 70 | 73 |
| 2030 MEDRES Miroc3.2 | Minimum | 101 | 109 | 83 | 146 | 155 | 106 | 145 | 227 | 91 | 33 | 39 | 41 | 34 | 33 | 44 | 51 | 61 | 51 |
| | Quartile 1 | 121 | 138 | 113 | 167 | 197 | 131 | 177 | 251 | 127 | 38 | 42 | 45 | 41 | 41 | 49 | 57 | 67 | 62 |
| | Median | 133 | 163 | 156 | 181 | 209 | 153 | 195 | 257 | 162 | 40 | 45 | 48 | 45 | 48 | 52 | 60 | 70 | 73 |
| | Quartile 2 | 140 | 194 | 178 | 191 | 222 | 188 | 217 | 264 | 214 | 41 | 53 | 53 | 51 | 50 | 54 | 64 | 73 | 79 |
| | Maximum | 156 | 221 | 241 | 233 | 239 | 232 | 242 | 271 | 296 | 45 | 60 | 63 | 58 | 56 | 61 | 74 | 75 | 96 |
| | Average | 131 | 165 | 151 | 180 | 207 | 160 | 195 | 256 | 167 | 39 | 47 | 49 | 46 | 45 | 52 | 61 | 70 | 71 |
| 2050 MEDRES Miroc3.2 | Minimum | 93 | 100 | 75 | 131 | 140 | 97 | 133 | 208 | 84 | 33 | 40 | 41 | 34 | 32 | 44 | 51 | 60 | 51 |
| | Quartile 1 | 112 | 126 | 102 | 150 | 179 | 120 | 162 | 230 | 117 | 39 | 43 | 46 | 42 | 40 | 49 | 56 | 66 | 61 |
| | Median | 122 | 148 | 140 | 163 | 190 | 140 | 179 | 236 | 149 | 41 | 46 | 48 | 45 | 47 | 51 | 59 | 69 | 71 |
| | Quartile 2 | 127 | 174 | 160 | 174 | 202 | 173 | 199 | 242 | 197 | 41 | 53 | 53 | 51 | 49 | 53 | 63 | 72 | 78 |
| | Maximum | 144 | 199 | 217 | 209 | 217 | 212 | 222 | 249 | 271 | 46 | 61 | 64 | 58 | 54 | 61 | 74 | 74 | 94 |
| | Average | 120 | 150 | 136 | 163 | 188 | 147 | 179 | 235 | 154 | 40 | 48 | 50 | 46 | 44 | 51 | 60 | 69 | 70 |
| 2070 MEDRES Miroc3.2 | Minimum | 87 | 94 | 69 | 121 | 129 | 91 | 125 | 195 | 79 | 34 | 40 | 41 | 33 | 32 | 44 | 50 | 60 | 50 |
| | Quartile 1 | 105 | 118 | 94 | 140 | 167 | 113 | 152 | 216 | 110 | 40 | 44 | 46 | 42 | 39 | 48 | 56 | 66 | 60 |
| | Median | 114 | 138 | 129 | 152 | 177 | 131 | 168 | 221 | 141 | 41 | 47 | 49 | 45 | 46 | 51 | 59 | 68 | 70 |
| | Quartile 2 | 119 | 161 | 148 | 162 | 188 | 162 | 186 | 227 | 186 | 42 | 54 | 54 | 51 | 48 | 53 | 63 | 71 | 77 |
| | Maximum | 135 | 184 | 200 | 193 | 202 | 199 | 208 | 234 | 255 | 46 | 61 | 64 | 59 | 53 | 60 | 73 | 73 | 92 |
| | Average | 112 | 139 | 126 | 152 | 175 | 138 | 168 | 220 | 145 | 41 | 49 | 50 | 46 | 44 | 51 | 60 | 68 | 69 |
| 2030 CSIRO Mk3.5 | Minimum | 82 | 80 | 78 | 132 | 167 | 102 | 145 | 205 | 83 | 27 | 32 | 36 | 31 | 29 | 42 | 48 | 57 | 48 |
| | Quartile 1 | 92 | 102 | 104 | 147 | 207 | 127 | 170 | 216 | 105 | 31 | 35 | 40 | 37 | 38 | 46 | 53 | 63 | 57 |
| | Median | 100 | 122 | 140 | 154 | 221 | 146 | 183 | 222 | 136 | 33 | 40 | 42 | 41 | 44 | 48 | 56 | 65 | 67 |
| | Quartile 2 | 109 | 146 | 158 | 162 | 227 | 164 | 195 | 225 | 181 | 35 | 47 | 47 | 46 | 46 | 50 | 60 | 68 | 73 |
| | Maximum | 133 | 180 | 180 | 210 | 240 | 202 | 210 | 230 | 263 | 40 | 53 | 55 | 51 | 51 | 58 | 70 | 70 | 89 |
| | Average | 101 | 125 | 133 | 156 | 215 | 147 | 181 | 220 | 141 | 33 | 41 | 43 | 41 | 42 | 48 | 57 | 65 | 66 |
| 2050 CSIRO Mk3.5 | Minimum | 53 | 52 | 58 | 97 | 150 | 80 | 118 | 168 | 56 | 22 | 27 | 32 | 28 | 25 | 39 | 45 | 53 | 43 |
| | Quartile 1 | 61 | 68 | 76 | 109 | 186 | 101 | 140 | 177 | 74 | 26 | 29 | 36 | 34 | 34 | 43 | 49 | 58 | 52 |
| | Median | 67 | 88 | 103 | 116 | 198 | 117 | 150 | 182 | 98 | 27 | 36 | 38 | 38 | 40 | 45 | 52 | 61 | 61 |
| | Quartile 2 | 75 | 108 | 117 | 124 | 205 | 134 | 159 | 184 | 141 | 29 | 42 | 42 | 41 | 42 | 47 | 56 | 63 | 67 |
| | Maximum | 98 | 133 | 133 | 184 | 218 | 167 | 172 | 189 | 215 | 36 | 47 | 50 | 46 | 47 | 53 | 65 | 65 | 80 |
| | Average | 69 | 89 | 98 | 120 | 194 | 119 | 148 | 180 | 103 | 28 | 36 | 39 | 37 | 38 | 45 | 53 | 61 | 60 |
| 2070 CSIRO Mk3.5 | Minimum | 23 | 23 | 36 | 60 | 132 | 56 | 90 | 128 | 26 | 18 | 21 | 28 | 24 | 21 | 36 | 41 | 49 | 38 |
| | Quartile 1 | 26 | 34 | 47 | 69 | 163 | 74 | 106 | 135 | 38 | 21 | 23 | 31 | 30 | 30 | 39 | 45 | 54 | 47 |
| | Median | 31 | 52 | 64 | 74 | 175 | 87 | 115 | 139 | 61 | 22 | 31 | 33 | 34 | 36 | 41 | 48 | 56 | 55 |
| | Quartile 2 | 40 | 67 | 73 | 87 | 183 | 102 | 122 | 140 | 100 | 23 | 36 | 36 | 37 | 38 | 43 | 51 | 58 | 61 |
| | Maximum | 61 | 83 | 83 | 156 | 195 | 130 | 131 | 144 | 164 | 31 | 41 | 43 | 42 | 42 | 49 | 60 | 60 | 73 |
| | Average | 34 | 51 | 61 | 81 | 171 | 88 | 113 | 138 | 64 | 23 | 30 | 34 | 33 | 34 | 41 | 49 | 56 | 54 |

†Wine regions: SD = Swan District, PH = Perth Hills, PL = Peel, GR-Geographe, MR = Margaret River, BW = Blackwood Valley, MJ = Manjimup, PM = Pemberton, GS = Great Southern

Projected changes in the summer rainfall vary little between low and high warming climate change ranges such that summer average rainfall is projected to increase slightly, about 2 to 3 mm for the four northern wine regions under low warming range, while the southern regions are projected to have as much as 4 mm less. This contrasts with at least a 15 mm projected decline for the northern wine regions for this season under the high warming range, clearly indicating some degree of inconsistency among the GCM projections for future rainfall (Table 4.9; Figure 4.14).

Table 4.10 Current and projected autumn (March to May) and winter (June to August) rainfall under SRES A2 emission scenario

| Year and Climate model | Statistics | Autumn Rainfall (mm) | | | | | | | | | Winter Rainfall (mm) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | †Wine regions | | | | | | | | | | | | | | | | | |
| | | SD | PH | PL | GR | MR | BW | MJ | PM | GS | SD | PH | PL | GR | MR | BW | MJ | PM | GS |
| 1990 | Minimum | 125 | 123 | 97 | 159 | 178 | 113 | 144 | 208 | 89 | 302 | 318 | 223 | 365 | 455 | 237 | 286 | 457 | 142 |
| | Quartile 1 | 144 | 144 | 126 | 182 | 207 | 136 | 168 | 231 | 122 | 368 | 384 | 303 | 454 | 529 | 284 | 353 | 525 | 198 |
| | Median | 150 | 165 | 173 | 190 | 218 | 156 | 184 | 240 | 157 | 394 | 468 | 449 | 475 | 549 | 345 | 392 | 557 | 270 |
| | Quartile 2 | 160 | 193 | 194 | 199 | 228 | 189 | 202 | 249 | 207 | 435 | 542 | 500 | 501 | 585 | 442 | 442 | 570 | 395 |
| | Maximum | 170 | 220 | 241 | 230 | 239 | 218 | 225 | 259 | 293 | 471 | 595 | 647 | 630 | 614 | 516 | 512 | 593 | 643 |
| | Average | 151 | 169 | 164 | 191 | 215 | 162 | 184 | 239 | 161 | 399 | 464 | 413 | 481 | 551 | 362 | 394 | 547 | 290 |
| 2030 MEDRES Miroc3.2 | Minimum | 126 | 124 | 97 | 158 | 171 | 111 | 141 | 205 | 89 | 279 | 294 | 206 | 337 | 421 | 220 | 266 | 425 | 133 |
| | Quartile 1 | 144 | 144 | 126 | 181 | 198 | 133 | 165 | 227 | 122 | 339 | 354 | 279 | 421 | 493 | 264 | 328 | 488 | 186 |
| | Median | 151 | 164 | 172 | 188 | 209 | 154 | 181 | 236 | 156 | 364 | 431 | 414 | 440 | 512 | 321 | 365 | 519 | 252 |
| | Quartile 2 | 160 | 192 | 193 | 198 | 218 | 186 | 199 | 245 | 206 | 401 | 500 | 461 | 463 | 546 | 412 | 411 | 531 | 369 |
| | Maximum | 170 | 219 | 240 | 229 | 229 | 214 | 221 | 255 | 289 | 434 | 548 | 597 | 581 | 572 | 480 | 477 | 552 | 598 |
| | Average | 151 | 169 | 163 | 189 | 206 | 159 | 181 | 235 | 160 | 368 | 428 | 381 | 445 | 514 | 337 | 367 | 510 | 271 |
| 2050 MEDRES Miroc3.2 | Minimum | 126 | 124 | 97 | 157 | 163 | 109 | 139 | 201 | 89 | 253 | 267 | 187 | 306 | 383 | 203 | 245 | 391 | 123 |
| | Quartile 1 | 145 | 145 | 125 | 178 | 189 | 131 | 162 | 223 | 122 | 308 | 322 | 253 | 385 | 455 | 243 | 302 | 449 | 172 |
| | Median | 151 | 164 | 172 | 186 | 199 | 151 | 178 | 232 | 156 | 331 | 392 | 376 | 404 | 472 | 295 | 335 | 477 | 233 |
| | Quartile 2 | 160 | 191 | 192 | 195 | 208 | 183 | 195 | 241 | 205 | 364 | 454 | 419 | 425 | 503 | 379 | 378 | 488 | 341 |
| | Maximum | 169 | 218 | 239 | 228 | 218 | 210 | 217 | 250 | 283 | 395 | 498 | 542 | 528 | 528 | 442 | 439 | 507 | 550 |
| | Average | 152 | 169 | 163 | 188 | 197 | 156 | 178 | 231 | 160 | 335 | 389 | 346 | 406 | 474 | 310 | 338 | 469 | 251 |
| 2070 MEDRES Miroc3.2 | Minimum | 127 | 125 | 96 | 157 | 157 | 108 | 137 | 198 | 89 | 236 | 249 | 174 | 285 | 358 | 191 | 231 | 368 | 117 |
| | Quartile 1 | 146 | 146 | 125 | 178 | 183 | 129 | 160 | 220 | 122 | 288 | 300 | 236 | 362 | 429 | 229 | 284 | 423 | 163 |
| | Median | 152 | 165 | 171 | 185 | 192 | 149 | 176 | 229 | 155 | 308 | 365 | 351 | 378 | 445 | 278 | 316 | 449 | 220 |
| | Quartile 2 | 160 | 191 | 192 | 194 | 201 | 181 | 193 | 238 | 203 | 340 | 423 | 390 | 398 | 475 | 356 | 356 | 460 | 322 |
| | Maximum | 169 | 218 | 239 | 228 | 211 | 208 | 214 | 247 | 280 | 368 | 464 | 506 | 492 | 498 | 416 | 413 | 478 | 518 |
| | Average | 152 | 169 | 162 | 187 | 190 | 154 | 176 | 228 | 159 | 312 | 363 | 323 | 380 | 447 | 292 | 318 | 441 | 237 |
| 2030 CSIRO Mk3.5 | Minimum | 124 | 116 | 108 | 169 | 181 | 121 | 154 | 211 | 105 | 288 | 304 | 215 | 351 | 422 | 219 | 265 | 423 | 130 |
| | Quartile 1 | 137 | 136 | 134 | 186 | 204 | 142 | 178 | 222 | 127 | 351 | 366 | 291 | 428 | 488 | 263 | 327 | 486 | 183 |
| | Median | 145 | 154 | 186 | 190 | 217 | 163 | 192 | 230 | 161 | 376 | 450 | 432 | 449 | 506 | 319 | 363 | 516 | 249 |
| | Quartile 2 | 153 | 180 | 199 | 196 | 219 | 182 | 201 | 237 | 208 | 417 | 522 | 481 | 477 | 540 | 409 | 409 | 528 | 366 |
| | Maximum | 171 | 214 | 216 | 211 | 222 | 213 | 218 | 252 | 289 | 453 | 572 | 623 | 606 | 566 | 477 | 474 | 549 | 595 |
| | Average | 145 | 159 | 170 | 191 | 211 | 163 | 189 | 230 | 166 | 382 | 446 | 398 | 457 | 508 | 335 | 365 | 507 | 267 |
| 2050 CSIRO Mk3.5 | Minimum | 120 | 112 | 107 | 166 | 167 | 117 | 146 | 199 | 104 | 276 | 291 | 207 | 339 | 394 | 204 | 246 | 393 | 121 |
| | Quartile 1 | 132 | 132 | 133 | 182 | 186 | 135 | 168 | 209 | 124 | 336 | 351 | 281 | 406 | 452 | 244 | 304 | 452 | 169 |
| | Median | 140 | 152 | 185 | 185 | 198 | 157 | 181 | 217 | 157 | 361 | 435 | 417 | 427 | 469 | 297 | 337 | 480 | 230 |
| | Quartile 2 | 149 | 178 | 197 | 191 | 199 | 174 | 190 | 224 | 201 | 402 | 504 | 465 | 456 | 500 | 381 | 380 | 491 | 339 |
| | Maximum | 169 | 212 | 214 | 209 | 204 | 200 | 205 | 238 | 273 | 438 | 553 | 602 | 586 | 525 | 444 | 441 | 510 | 553 |
| | Average | 141 | 156 | 169 | 187 | 192 | 155 | 178 | 216 | 161 | 367 | 430 | 384 | 435 | 471 | 312 | 339 | 471 | 248 |
| 2070 CSIRO Mk3.5 | Minimum | 115 | 108 | 106 | 163 | 151 | 110 | 136 | 186 | 103 | 263 | 277 | 199 | 327 | 363 | 187 | 226 | 362 | 110 |
| | Quartile 1 | 127 | 129 | 132 | 175 | 168 | 127 | 157 | 196 | 121 | 321 | 334 | 271 | 379 | 414 | 225 | 279 | 415 | 155 |
| | Median | 135 | 150 | 183 | 180 | 177 | 148 | 169 | 202 | 152 | 344 | 418 | 402 | 404 | 429 | 273 | 310 | 441 | 210 |
| | Quartile 2 | 145 | 176 | 196 | 189 | 178 | 165 | 177 | 209 | 192 | 384 | 485 | 447 | 439 | 458 | 350 | 350 | 451 | 310 |
| | Maximum | 168 | 210 | 212 | 207 | 184 | 187 | 192 | 222 | 255 | 422 | 532 | 579 | 563 | 480 | 408 | 406 | 469 | 509 |
| | Average | 136 | 153 | 167 | 182 | 173 | 146 | 166 | 202 | 156 | 350 | 412 | 370 | 412 | 431 | 287 | 312 | 433 | 226 |

†Wine regions: SD-Swan District, PH-Perth Hills, PL-Peel, GR-Geographe, MR-Margaret River, BW-Black Wood, MJ-Manjimup, PM-Pemberton, GS-Great Southern

Monthly distribution of future rainfall is projected to be more or less the same as under the current climate, with the exception of the Margaret River region where May is projected to receive a similar amount of rainfall as July by 2050 and 2070 (Figure 4.17).

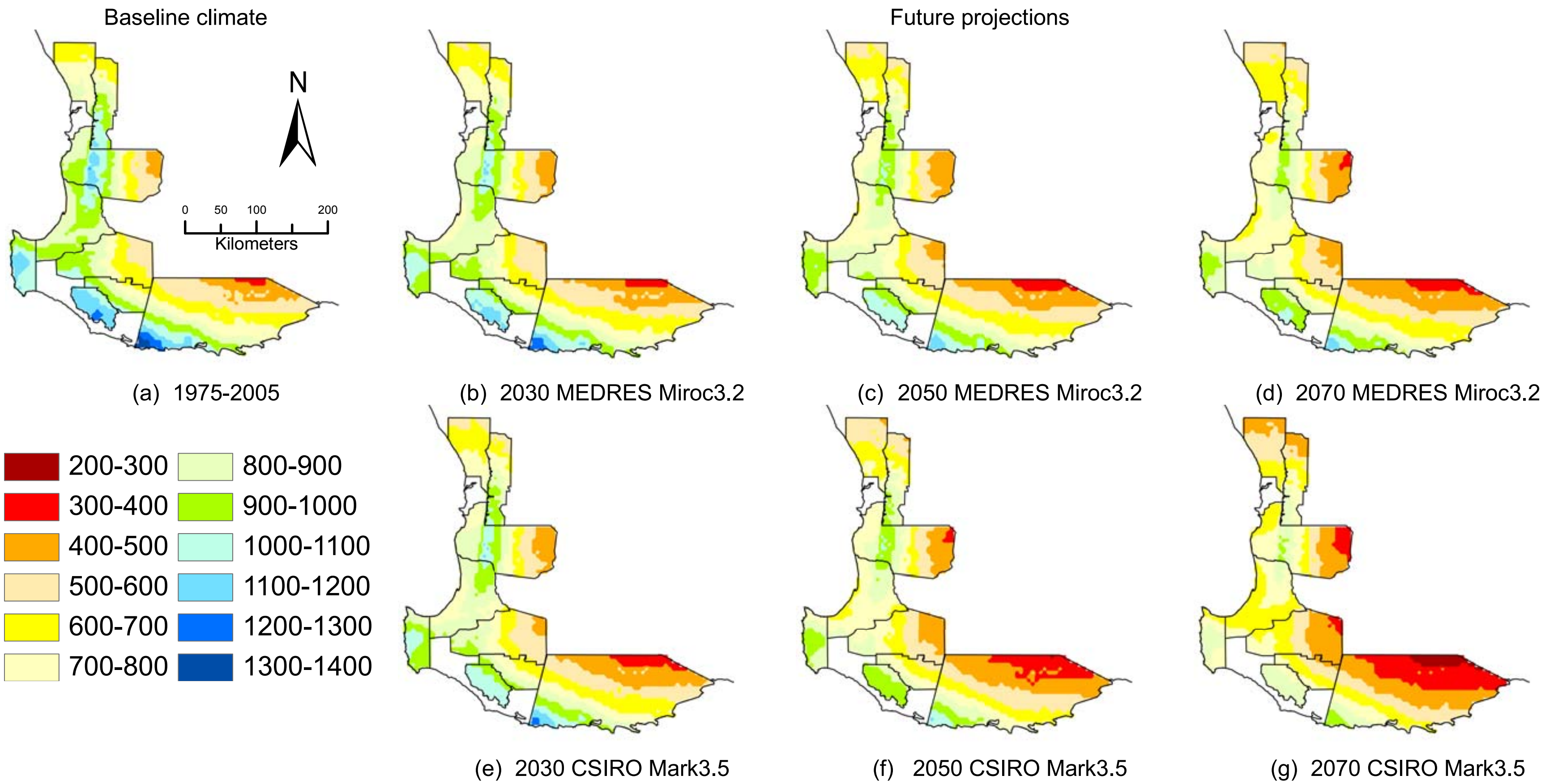


Figure 4.11 Current and projected annual rainfall (mm) under SRES A2 emission scenario

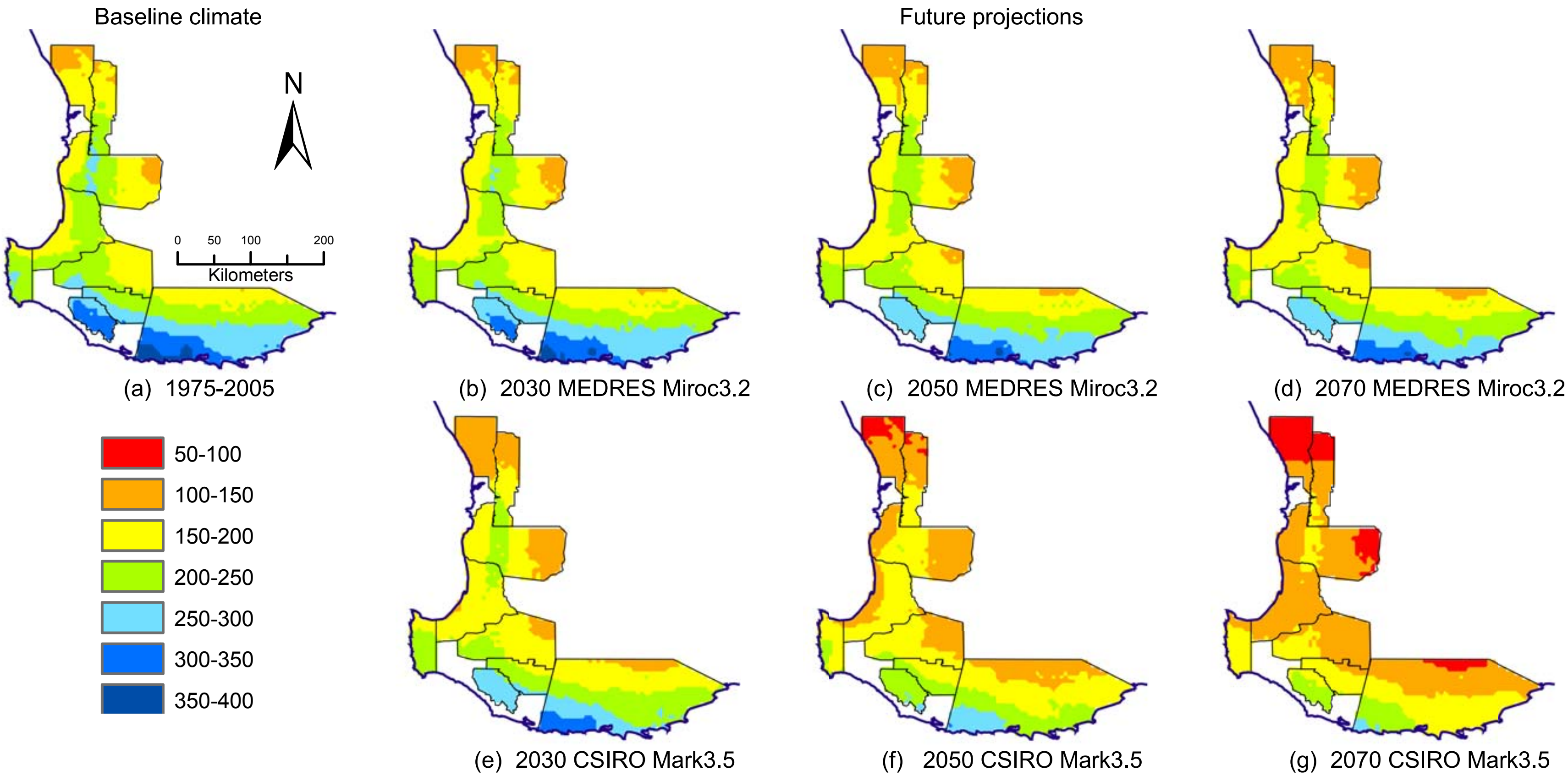


Figure 4.12 Current and projected rainfall during October to April (mm) under SRES A2 emission scenario

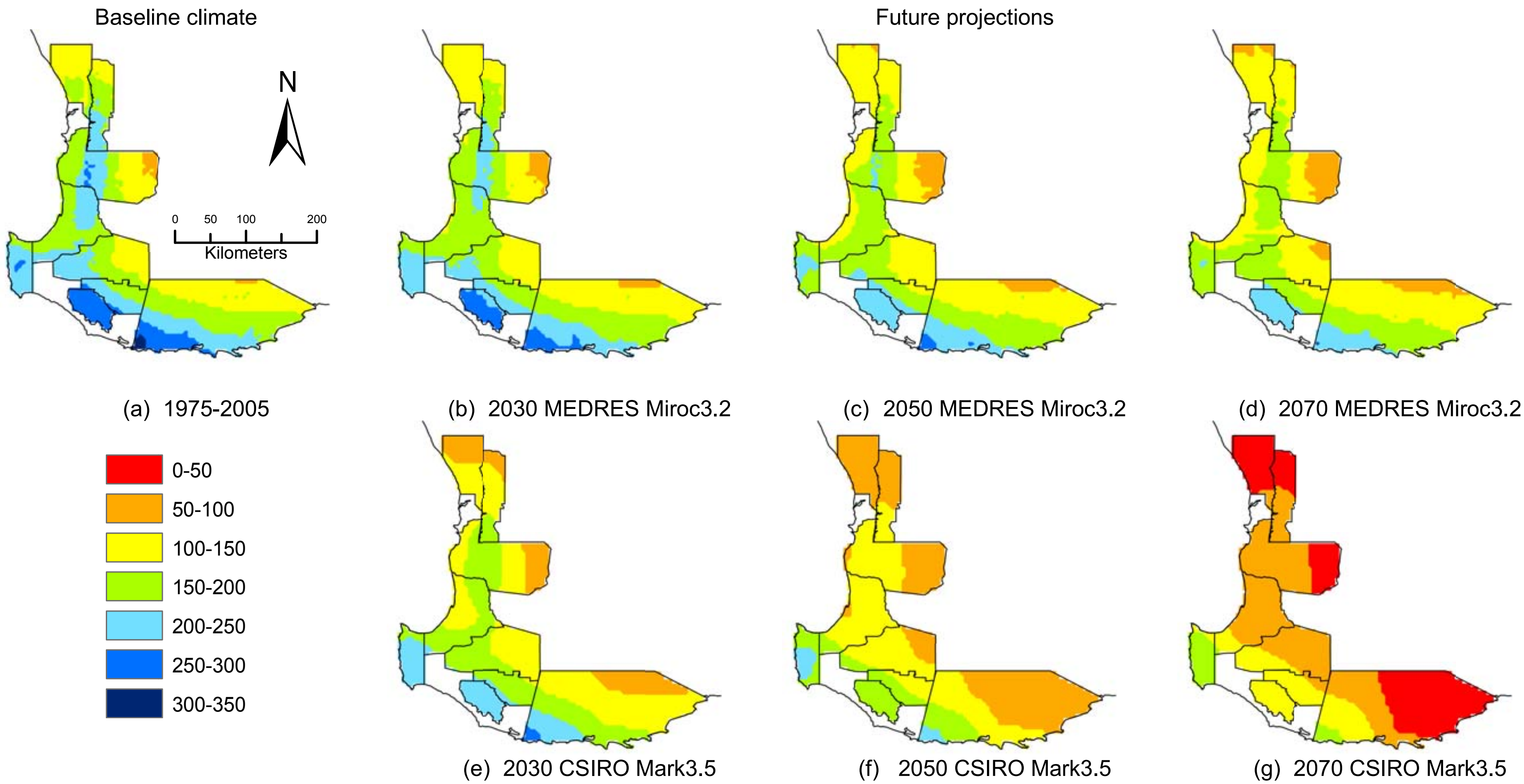


Figure 4.13 Current and projected rainfall during September to November (mm) under SRES A2 emission scenario

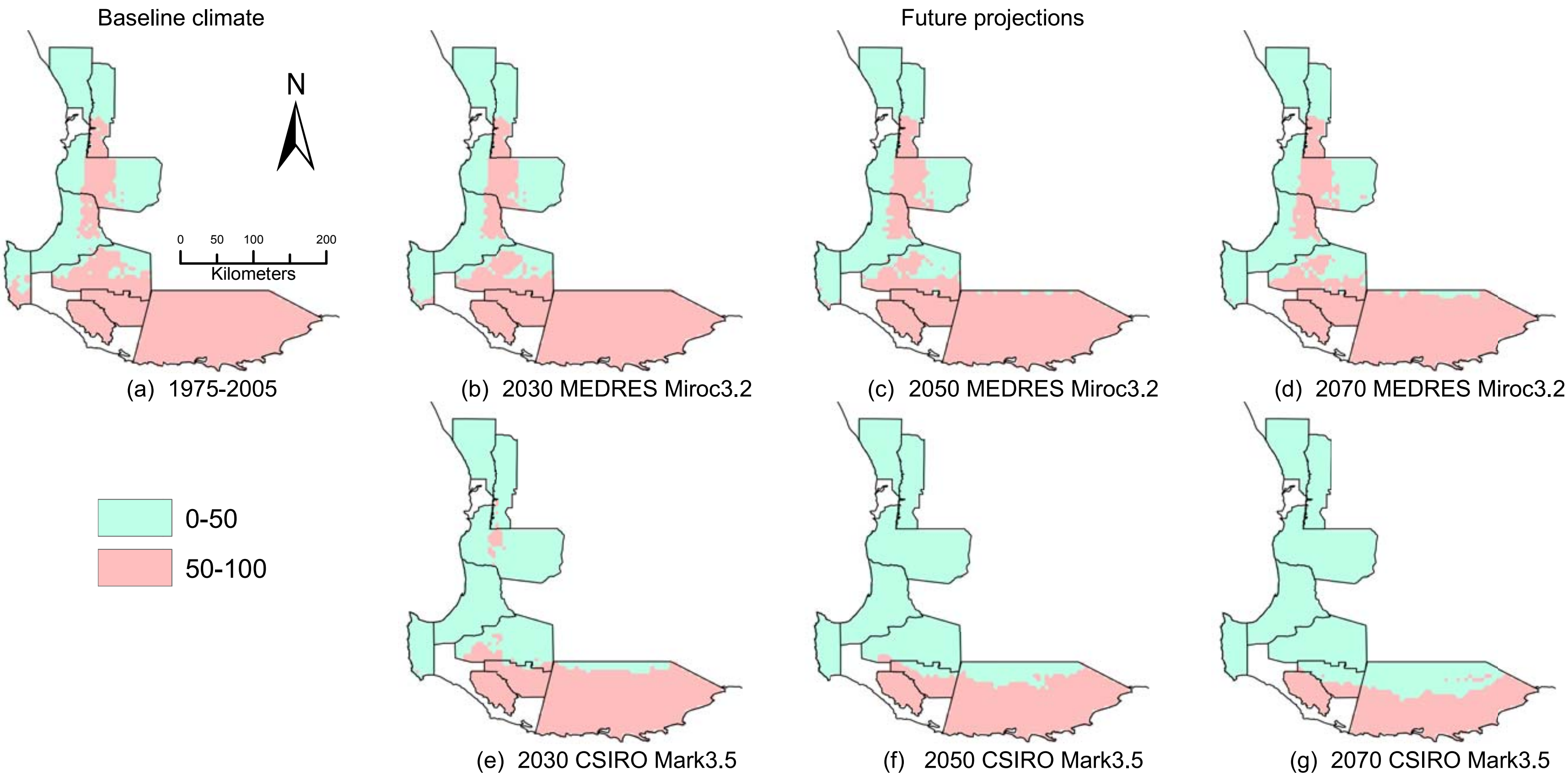


Figure 4.14 Current and projected rainfall during December to February (mm) under SRES A2 emission scenario

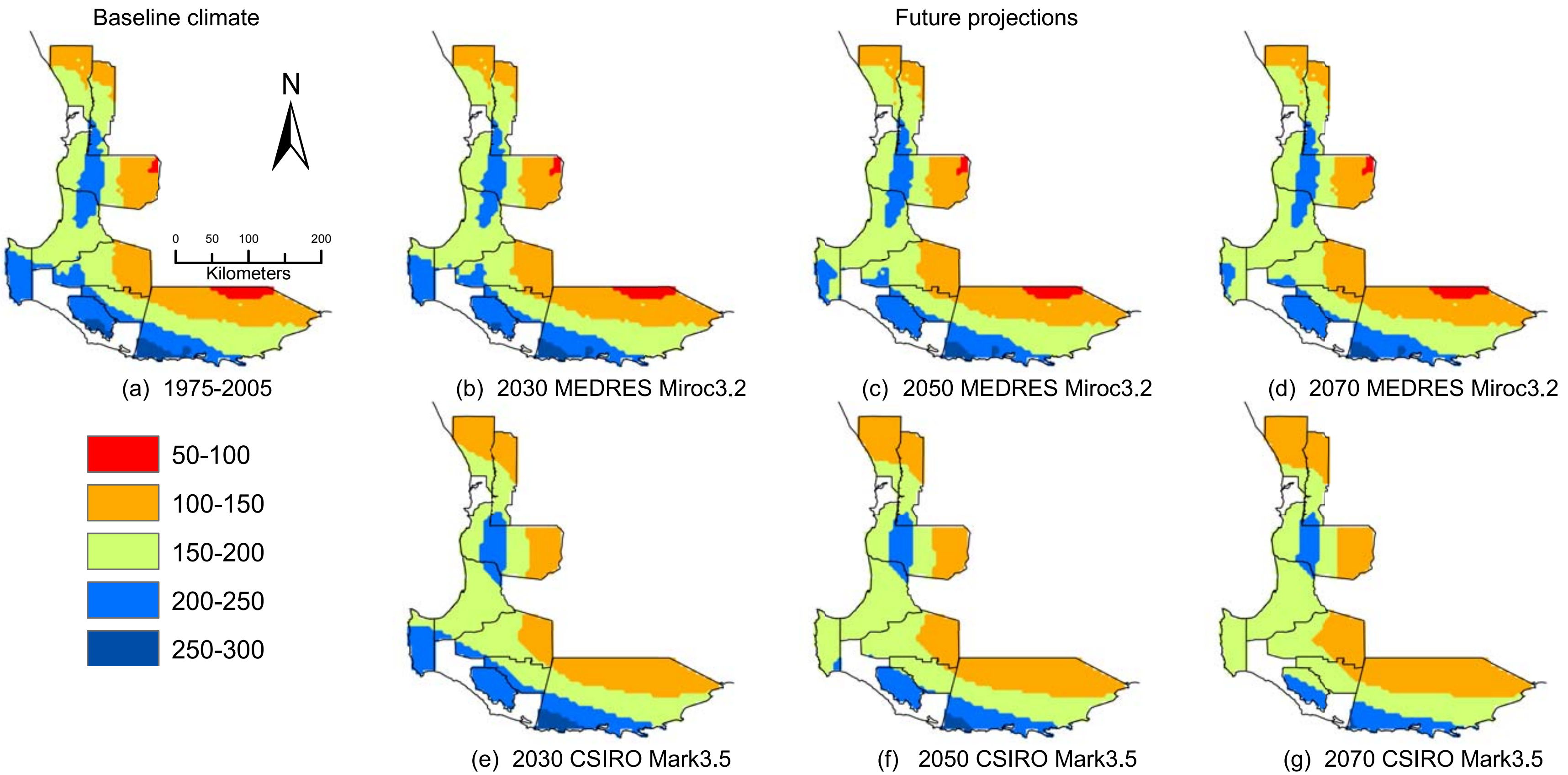


Figure 4.15 Current and projected rainfall during March to May (mm) under SRES A2 emission scenario

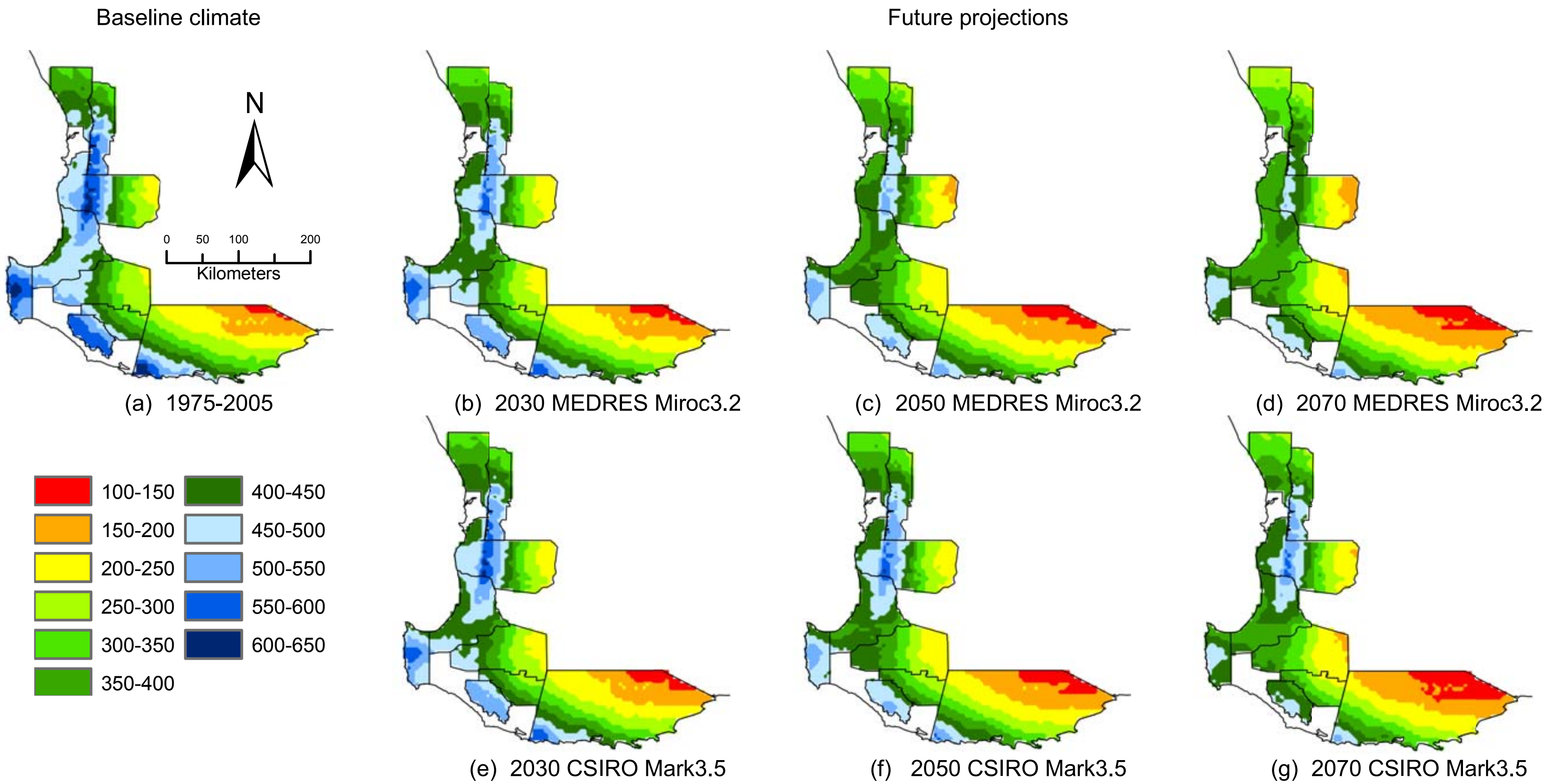


Figure 4.16 Current and projected rainfall during June to August (mm) under SRES A2 emission scenario

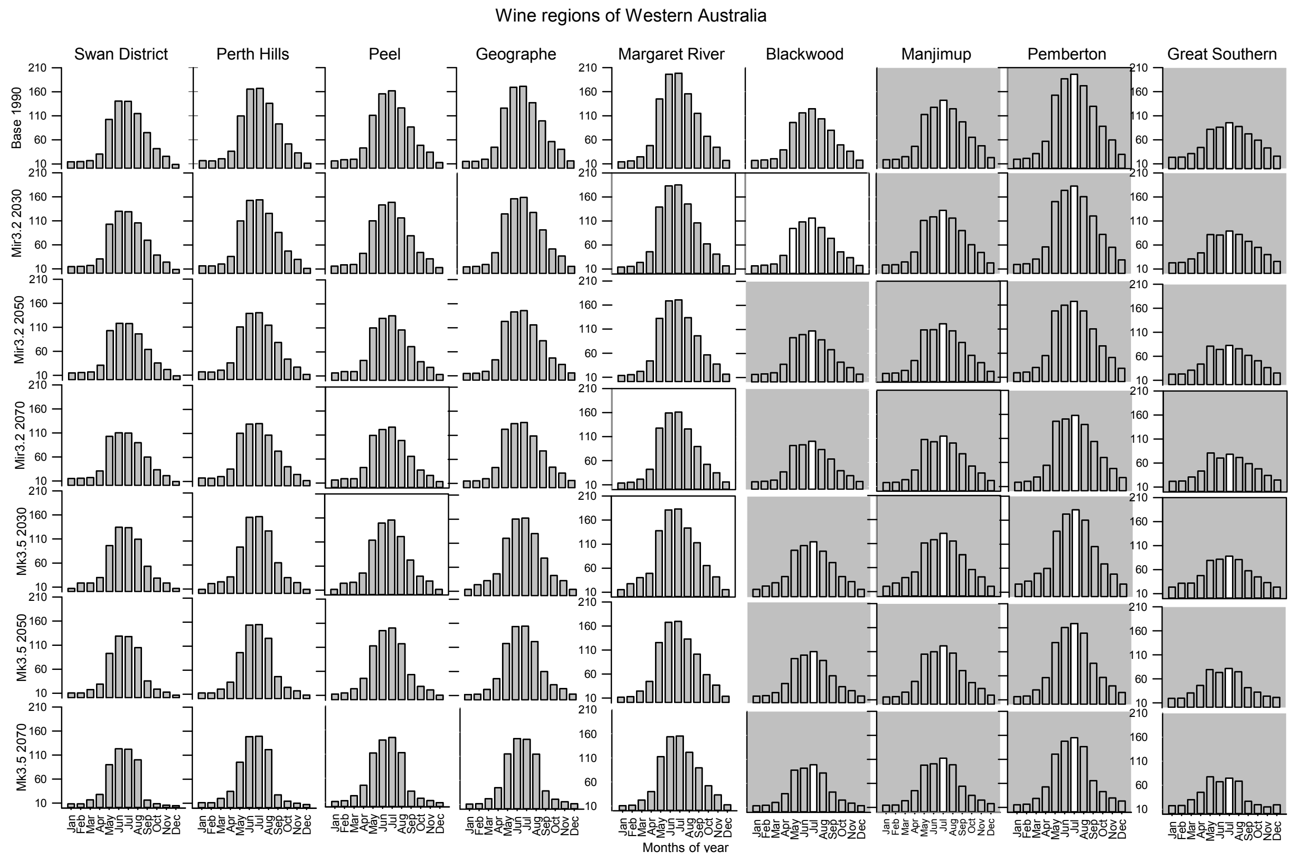


Figure 4.17 Temporal distributions of current and projected rainfall across Western Australian wine regions projected by Miroc3.2 and Mark3.5 global climate models under SRES A2 emission scenario.

### 4.3.11 Changes in the radiation

Magnitude of the radiation changes under climate change is small. The biggest projected changes among the radiation indices examined were an average of 6% increase across the Great Southern region for the July to September period, followed by a 5% increase in the October to November radiation under low warming climate change range by 2070 (Table 4.12, Figure 4.18 to 4.21). The maximum difference in radiation under high warming is about 2% increase for Margaret River, Blackwood, and the southern regions by 2070 (Table 4.11, 4.12; Figures 4.18 to 4.21).

Changes in the radiation indices were season and area specific under the same climate change ranges. For example, the current spatial distribution of December to February radiation remained relatively stable over time under low warming range (Figure 4.19 a-d) whereas July to September radiation changed considerably across the regions under the same climate change warming range (Figure 4.21 a-d). In addition and in contrast with the temperature related climate indices, the changes in the radiation indices tended to be lower in the northern regions compared to the southern wine regions when they were averaged for an entire region (Table 4.11 and 4.12; Figure 4.18 to 4.21).

Table 4.11 Current and projected total radiation (MJ/m$^2$) during October to November and December to February under SRES A2 emission scenario

| Year and Climate model | Statistics | Radiation October to November (†Wine regions) | | | | | | | | | Radiation December to February (†Wine regions) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | SD | PH | PL | GR | MR | BW | MJ | PM | GS | SD | PH | PL | GR | MR | BW | MJ | PM | GS |
| 1990 | Minimum | 46.8 | 45.2 | 43.5 | 41.5 | 40.2 | 40.5 | 39.8 | 39.8 | 39.2 | 79.3 | 78.3 | 76.2 | 73.9 | 70.7 | 71.5 | 70.0 | 69.7 | 67.4 |
| | Quartile 1 | 47.2 | 46.2 | 44.4 | 42.4 | 40.8 | 41.0 | 40.2 | 39.9 | 40.1 | 79.6 | 79.3 | 77.4 | 75.6 | 72.2 | 73.0 | 70.8 | 70.2 | 68.8 |
| | Median | 47.3 | 46.7 | 44.9 | 42.9 | 41.3 | 41.4 | 40.4 | 40.0 | 40.6 | 79.8 | 79.5 | 77.9 | 76.5 | 73.2 | 73.8 | 71.3 | 70.6 | 69.5 |
| | Quartile 2 | 47.5 | 47.3 | 45.2 | 43.7 | 41.8 | 41.8 | 40.5 | 40.2 | 41.2 | 79.9 | 79.8 | 78.6 | 77.3 | 74.2 | 74.5 | 71.8 | 71.1 | 70.3 |
| | Maximum | 47.7 | 47.6 | 46.6 | 44.9 | 42.5 | 42.4 | 40.8 | 40.5 | 42.0 | 80.2 | 80.0 | 79.8 | 78.4 | 75.4 | 75.5 | 72.6 | 71.8 | 71.6 |
| | Average | 47.3 | 46.7 | 44.9 | 43.1 | 41.3 | 41.4 | 40.4 | 40.1 | 40.6 | 79.7 | 79.5 | 78.0 | 76.4 | 73.2 | 73.7 | 71.4 | 70.7 | 69.5 |
| 2030 | Minimum | 47.2 | 46.1 | 44.1 | 42.3 | 41.1 | 41.5 | 40.9 | 40.7 | 40.5 | 79.4 | 78.9 | 76.5 | 74.2 | 71.3 | 72.0 | 70.7 | 70.1 | 68.2 |
| MEDRES | Quartile 1 | 47.7 | 46.9 | 44.8 | 43.1 | 41.6 | 42.0 | 41.1 | 40.9 | 41.0 | 79.8 | 79.6 | 77.4 | 75.7 | 72.6 | 73.5 | 71.2 | 70.8 | 69.3 |
| Miroc3.2 | Median | 47.9 | 47.5 | 45.3 | 43.5 | 42.1 | 42.2 | 41.3 | 40.9 | 41.6 | 79.9 | 79.9 | 78.0 | 76.5 | 73.5 | 74.1 | 71.7 | 71.1 | 70.0 |
| | Quartile 2 | 48.0 | 47.9 | 45.7 | 44.2 | 42.5 | 42.5 | 41.5 | 41.1 | 42.1 | 79.9 | 80.0 | 78.6 | 77.3 | 74.4 | 74.7 | 72.4 | 71.6 | 70.7 |
| | Maximum | 48.2 | 48.2 | 46.8 | 45.3 | 43.2 | 43.0 | 41.7 | 41.4 | 42.8 | 80.0 | 80.2 | 79.5 | 78.5 | 75.5 | 75.8 | 73.3 | 72.3 | 72.0 |
| | Average | 47.9 | 47.4 | 45.3 | 43.6 | 42.1 | 42.3 | 41.3 | 41.0 | 41.5 | 79.8 | 79.8 | 78.0 | 76.5 | 73.5 | 74.1 | 71.8 | 71.2 | 70.0 |
| 2050 | Minimum | 47.5 | 46.4 | 44.4 | 42.8 | 41.5 | 41.9 | 41.3 | 41.1 | 40.9 | 79.6 | 79.0 | 76.6 | 74.4 | 71.6 | 72.1 | 70.8 | 70.3 | 68.3 |
| MEDRES | Quartile 1 | 48.0 | 47.2 | 45.0 | 43.4 | 42.1 | 42.4 | 41.5 | 41.3 | 41.5 | 79.8 | 79.6 | 77.5 | 75.9 | 72.9 | 73.7 | 71.3 | 71.0 | 69.5 |
| Miroc3.2 | Median | 48.2 | 47.8 | 45.6 | 43.8 | 42.5 | 42.7 | 41.7 | 41.3 | 42.0 | 80.0 | 80.0 | 78.0 | 76.6 | 73.8 | 74.3 | 72.0 | 71.3 | 70.2 |
| | Quartile 2 | 48.3 | 48.2 | 46.0 | 44.4 | 42.9 | 42.9 | 41.9 | 41.5 | 42.6 | 80.1 | 80.1 | 78.7 | 77.4 | 74.5 | 74.9 | 72.6 | 71.8 | 70.9 |
| | Maximum | 48.5 | 48.5 | 47.1 | 45.6 | 43.5 | 43.3 | 42.2 | 41.8 | 43.3 | 80.3 | 80.3 | 79.7 | 78.5 | 75.7 | 75.9 | 73.4 | 72.4 | 72.3 |
| | Average | 48.1 | 47.6 | 45.6 | 43.9 | 42.5 | 42.7 | 41.7 | 41.4 | 42.0 | 80.0 | 79.9 | 78.1 | 76.6 | 73.7 | 74.2 | 72.0 | 71.4 | 70.2 |
| 2070 | Minimum | 47.8 | 46.7 | 44.6 | 43.2 | 41.9 | 42.4 | 41.8 | 41.6 | 41.3 | 79.7 | 79.1 | 76.6 | 74.5 | 71.7 | 72.3 | 71.0 | 70.6 | 68.6 |
| MEDRES | Quartile 1 | 48.3 | 47.5 | 45.3 | 43.7 | 42.5 | 42.8 | 41.9 | 41.7 | 41.9 | 80.0 | 79.7 | 77.6 | 76.0 | 73.1 | 73.9 | 71.6 | 71.1 | 69.7 |
| Miroc3.2 | Median | 48.5 | 48.1 | 45.9 | 44.1 | 43.0 | 43.1 | 42.2 | 41.8 | 42.5 | 80.1 | 80.1 | 78.2 | 76.8 | 73.9 | 74.5 | 72.1 | 71.5 | 70.4 |
| | Quartile 2 | 48.6 | 48.5 | 46.3 | 44.7 | 43.3 | 43.3 | 42.3 | 41.9 | 43.1 | 80.2 | 80.2 | 78.8 | 77.5 | 74.8 | 75.0 | 72.8 | 71.9 | 71.0 |
| | Maximum | 48.8 | 48.8 | 47.4 | 45.9 | 43.8 | 43.6 | 42.6 | 42.2 | 43.7 | 80.3 | 80.4 | 79.7 | 78.7 | 75.8 | 75.9 | 73.6 | 72.7 | 72.3 |
| | Average | 48.5 | 47.9 | 45.9 | 44.2 | 42.9 | 43.1 | 42.2 | 41.8 | 42.5 | 80.1 | 80.0 | 78.2 | 76.7 | 73.9 | 74.4 | 72.2 | 71.5 | 70.3 |
| 2030 | Minimum | 46.8 | 45.7 | 43.7 | 41.7 | 40.4 | 40.9 | 40.3 | 40.1 | 39.9 | 79.7 | 79.0 | 76.6 | 74.0 | 71.2 | 71.7 | 70.4 | 70.0 | 68.2 |
| CSIRO | Quartile 1 | 47.2 | 46.4 | 44.4 | 42.6 | 41.0 | 41.3 | 40.5 | 40.2 | 40.4 | 80.0 | 79.7 | 77.6 | 75.7 | 72.5 | 73.3 | 71.0 | 70.6 | 69.2 |
| Mk3.5 | Median | 47.4 | 47.0 | 44.9 | 43.1 | 41.5 | 41.6 | 40.7 | 40.3 | 40.9 | 80.1 | 80.1 | 78.1 | 76.6 | 73.5 | 73.9 | 71.5 | 70.9 | 69.9 |
| | Quartile 2 | 47.5 | 47.4 | 45.3 | 43.7 | 41.9 | 42.0 | 40.9 | 40.5 | 41.5 | 80.2 | 80.3 | 78.7 | 77.4 | 74.2 | 74.5 | 72.1 | 71.3 | 70.5 |
| | Maximum | 47.7 | 47.7 | 46.4 | 44.9 | 42.7 | 42.5 | 41.1 | 40.7 | 42.1 | 80.3 | 80.4 | 79.7 | 78.6 | 75.5 | 75.8 | 73.0 | 72.0 | 71.8 |
| | Average | 47.4 | 46.9 | 44.9 | 43.1 | 41.5 | 41.7 | 40.7 | 40.4 | 40.9 | 80.1 | 80.0 | 78.1 | 76.5 | 73.4 | 73.9 | 71.6 | 71.0 | 69.9 |
| 2050 | Minimum | 46.9 | 45.8 | 43.8 | 41.9 | 40.6 | 41.1 | 40.5 | 40.3 | 40.0 | 80.0 | 79.4 | 76.9 | 74.2 | 71.3 | 71.8 | 70.5 | 70.1 | 68.4 |
| CSIRO | Quartile 1 | 47.3 | 46.5 | 44.5 | 42.7 | 41.2 | 41.5 | 40.6 | 40.4 | 40.6 | 80.4 | 80.0 | 77.9 | 76.0 | 72.6 | 73.4 | 71.0 | 70.7 | 69.4 |
| Mk3.5 | Median | 47.4 | 47.1 | 45.0 | 43.2 | 41.6 | 41.8 | 40.9 | 40.5 | 41.1 | 80.5 | 80.4 | 78.4 | 76.9 | 73.5 | 74.1 | 71.7 | 71.0 | 70.1 |
| | Quartile 2 | 47.6 | 47.4 | 45.4 | 43.8 | 42.1 | 42.1 | 41.0 | 40.6 | 41.7 | 80.6 | 80.6 | 79.1 | 77.7 | 74.5 | 74.7 | 72.3 | 71.5 | 70.9 |
| | Maximum | 47.8 | 47.7 | 46.5 | 45.0 | 42.8 | 42.6 | 41.3 | 40.9 | 42.4 | 80.7 | 80.8 | 80.0 | 79.0 | 75.7 | 76.0 | 73.2 | 72.2 | 72.0 |
| | Average | 47.4 | 47.0 | 45.0 | 43.3 | 41.6 | 41.8 | 40.9 | 40.5 | 41.1 | 80.5 | 80.3 | 78.5 | 76.8 | 73.5 | 74.0 | 71.7 | 71.1 | 70.1 |
| 2070 | Minimum | 47.0 | 45.9 | 43.9 | 42.0 | 40.8 | 41.3 | 40.7 | 40.5 | 40.2 | 80.4 | 79.7 | 77.2 | 74.4 | 71.6 | 72.0 | 70.7 | 70.1 | 68.7 |
| CSIRO | Quartile 1 | 47.4 | 46.6 | 44.6 | 42.8 | 41.3 | 41.7 | 40.8 | 40.6 | 40.8 | 80.8 | 80.3 | 78.2 | 76.2 | 72.8 | 73.5 | 71.2 | 70.8 | 69.6 |
| Mk3.5 | Median | 47.5 | 47.2 | 45.1 | 43.3 | 41.8 | 42.0 | 41.0 | 40.7 | 41.3 | 80.9 | 80.8 | 78.8 | 77.3 | 73.8 | 74.2 | 71.8 | 71.1 | 70.4 |
| | Quartile 2 | 47.6 | 47.5 | 45.5 | 43.9 | 42.2 | 42.3 | 41.2 | 40.8 | 41.9 | 81.0 | 81.1 | 79.4 | 78.1 | 74.6 | 74.9 | 72.4 | 71.6 | 71.1 |
| | Maximum | 47.8 | 47.8 | 46.6 | 45.1 | 42.8 | 42.7 | 41.5 | 41.1 | 42.6 | 81.2 | 81.3 | 80.3 | 79.3 | 75.8 | 76.2 | 73.3 | 72.3 | 72.0 |
| | Average | 47.5 | 47.1 | 45.1 | 43.4 | 41.8 | 42.0 | 41.0 | 40.7 | 41.3 | 80.9 | 80.7 | 78.8 | 77.1 | 73.7 | 74.2 | 71.8 | 71.2 | 70.4 |

†Wine regions: SD = Swan District, PH = Perth Hills, PL = Peel, GR-Geographe, MR = Margaret River, BW = Blackwood Valley, MJ = Manjimup, PM = Pemberton, GS = Great Southern

Table 4.12 Current and projected total radiation ($MJ/m^2$) during March to June and July to September under SRES A2 emission scenario

| Year and Climate model | Statistics | Radiation March to June | | | | | | | | | Radiation July to September | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | †Wine regions | | | | | | | | | | | | | | | | | |
| | | SD | PH | PL | GR | MR | BW | MJ | PM | GS | SD | PH | PL | GR | MR | BW | MJ | PM | GS |
| 1990 | Minimum | 57.6 | 55.4 | 53.3 | 50.7 | 48.7 | 49.9 | 48.8 | 48.7 | 47.8 | 41.8 | 39.7 | 38.3 | 36.0 | 34.8 | 35.5 | 35.3 | 35.2 | 34.9 |
| | Quartile 1 | 58.3 | 56.8 | 54.5 | 52.2 | 49.7 | 50.5 | 49.4 | 48.9 | 49.0 | 42.5 | 41.1 | 39.1 | 37.0 | 35.4 | 36.2 | 35.7 | 35.3 | 36.2 |
| | Median | 58.5 | 57.5 | 55.0 | 52.8 | 50.3 | 51.0 | 49.7 | 49.1 | 49.5 | 42.7 | 41.8 | 39.5 | 37.6 | 35.7 | 36.5 | 35.9 | 35.4 | 36.9 |
| | Quartile 2 | 58.6 | 58.3 | 55.4 | 53.7 | 50.9 | 51.5 | 49.9 | 49.4 | 50.2 | 43.0 | 42.6 | 39.9 | 38.3 | 36.1 | 36.9 | 36.0 | 35.5 | 37.6 |
| | Maximum | 58.9 | 58.8 | 57.2 | 55.0 | 51.8 | 52.3 | 50.2 | 49.7 | 51.0 | 43.3 | 43.1 | 41.4 | 39.4 | 36.8 | 37.5 | 36.2 | 35.8 | 38.7 |
| | Average | 58.4 | 57.5 | 55.0 | 52.9 | 50.3 | 51.0 | 49.6 | 49.2 | 49.6 | 42.7 | 41.7 | 39.5 | 37.7 | 35.8 | 36.5 | 35.8 | 35.4 | 36.9 |
| 2030 MEDRES Miroc3.2 | Minimum | 58.0 | 56.4 | 54.0 | 51.4 | 49.5 | 50.6 | 49.8 | 49.3 | 49.0 | 42.2 | 40.7 | 38.7 | 36.7 | 35.6 | 36.5 | 36.3 | 35.9 | 36.0 |
| | Quartile 1 | 58.7 | 57.5 | 54.7 | 52.7 | 50.4 | 51.3 | 50.1 | 49.7 | 49.7 | 43.0 | 41.7 | 39.4 | 37.7 | 36.1 | 37.0 | 36.5 | 36.0 | 37.0 |
| | Median | 59.0 | 58.3 | 55.4 | 53.4 | 50.9 | 51.7 | 50.4 | 49.9 | 50.3 | 43.3 | 42.6 | 39.9 | 38.2 | 36.4 | 37.2 | 36.6 | 36.1 | 37.6 |
| | Quartile 2 | 59.2 | 58.9 | 55.9 | 54.1 | 51.5 | 52.1 | 50.7 | 50.1 | 50.9 | 43.6 | 43.3 | 40.4 | 38.7 | 36.8 | 37.5 | 36.7 | 36.3 | 38.3 |
| | Maximum | 59.4 | 59.4 | 57.4 | 55.4 | 52.6 | 52.8 | 51.2 | 50.5 | 51.5 | 43.9 | 43.8 | 41.6 | 39.8 | 37.5 | 37.9 | 36.9 | 36.5 | 39.3 |
| | Average | 58.9 | 58.2 | 55.4 | 53.4 | 51.0 | 51.7 | 50.4 | 49.9 | 50.3 | 43.3 | 42.5 | 39.9 | 38.2 | 36.4 | 37.2 | 36.6 | 36.2 | 37.7 |
| 2050 MEDRES Miroc3.2 | Minimum | 58.4 | 56.8 | 54.3 | 51.7 | 49.8 | 51.1 | 50.2 | 49.7 | 49.3 | 42.8 | 41.3 | 39.3 | 37.4 | 36.3 | 37.2 | 37.0 | 36.6 | 36.7 |
| | Quartile 1 | 59.2 | 58.0 | 55.2 | 53.1 | 50.7 | 51.7 | 50.5 | 50.1 | 50.1 | 43.6 | 42.4 | 40.0 | 38.3 | 36.8 | 37.7 | 37.2 | 36.7 | 37.8 |
| | Median | 59.4 | 58.7 | 55.8 | 53.8 | 51.3 | 52.1 | 50.8 | 50.3 | 50.7 | 44.0 | 43.2 | 40.5 | 38.7 | 37.1 | 37.9 | 37.3 | 36.9 | 38.4 |
| | Quartile 2 | 59.7 | 59.5 | 56.3 | 54.5 | 52.0 | 52.5 | 51.1 | 50.5 | 51.3 | 44.2 | 43.9 | 40.9 | 39.3 | 37.5 | 38.2 | 37.4 | 37.0 | 39.1 |
| | Maximum | 59.9 | 59.9 | 57.8 | 55.9 | 53.0 | 53.2 | 51.6 | 50.9 | 51.9 | 44.5 | 44.4 | 42.2 | 40.4 | 38.1 | 38.5 | 37.6 | 37.2 | 40.1 |
| | Average | 59.4 | 58.7 | 55.8 | 53.8 | 51.3 | 52.1 | 50.8 | 50.3 | 50.7 | 43.9 | 43.1 | 40.5 | 38.8 | 37.1 | 37.9 | 37.3 | 36.9 | 38.4 |
| 2070 MEDRES Miroc3.2 | Minimum | 58.8 | 57.2 | 54.7 | 52.1 | 50.2 | 51.4 | 50.6 | 50.1 | 49.7 | 43.2 | 41.7 | 39.7 | 37.9 | 36.7 | 37.6 | 37.5 | 37.0 | 37.2 |
| | Quartile 1 | 59.5 | 58.4 | 55.5 | 53.5 | 51.1 | 52.1 | 50.9 | 50.4 | 50.5 | 44.0 | 42.8 | 40.4 | 38.7 | 37.2 | 38.2 | 37.7 | 37.2 | 38.3 |
| | Median | 59.8 | 59.1 | 56.1 | 54.1 | 51.7 | 52.5 | 51.2 | 50.6 | 51.1 | 44.4 | 43.6 | 40.9 | 39.1 | 37.5 | 38.4 | 37.8 | 37.3 | 38.9 |
| | Quartile 2 | 60.1 | 59.9 | 56.7 | 54.9 | 52.3 | 52.8 | 51.4 | 50.9 | 51.7 | 44.7 | 44.3 | 41.4 | 39.7 | 37.9 | 38.6 | 37.9 | 37.4 | 39.7 |
| | Maximum | 60.3 | 60.3 | 58.2 | 56.2 | 53.3 | 53.6 | 52.0 | 51.3 | 52.4 | 44.9 | 44.8 | 42.7 | 40.8 | 38.5 | 39.0 | 38.1 | 37.7 | 40.6 |
| | Average | 59.8 | 59.0 | 56.1 | 54.1 | 51.7 | 52.5 | 51.2 | 50.7 | 51.1 | 44.3 | 43.5 | 40.9 | 39.2 | 37.6 | 38.4 | 37.8 | 37.3 | 39.0 |
| 2030 CSIRO Mk3.5 | Minimum | 57.5 | 56.0 | 53.6 | 50.9 | 49.1 | 50.1 | 49.3 | 48.7 | 48.4 | 41.8 | 40.3 | 38.4 | 36.3 | 35.2 | 36.0 | 35.9 | 35.5 | 35.6 |
| | Quartile 1 | 58.2 | 57.0 | 54.3 | 52.2 | 49.9 | 50.7 | 49.6 | 49.1 | 49.2 | 42.5 | 41.3 | 39.1 | 37.3 | 35.7 | 36.5 | 36.1 | 35.6 | 36.5 |
| | Median | 58.6 | 57.9 | 54.9 | 52.9 | 50.6 | 51.1 | 49.9 | 49.3 | 49.7 | 42.9 | 42.1 | 39.5 | 37.8 | 36.0 | 36.8 | 36.2 | 35.7 | 37.2 |
| | Quartile 2 | 58.8 | 58.5 | 55.4 | 53.6 | 51.2 | 51.5 | 50.2 | 49.6 | 50.3 | 43.1 | 42.8 | 40.0 | 38.3 | 36.5 | 37.1 | 36.3 | 35.9 | 37.8 |
| | Maximum | 59.0 | 59.0 | 56.9 | 55.0 | 52.1 | 52.3 | 50.6 | 50.0 | 51.0 | 43.4 | 43.3 | 41.2 | 39.4 | 37.2 | 37.5 | 36.4 | 36.1 | 38.8 |
| | Average | 58.5 | 57.8 | 54.9 | 52.9 | 50.6 | 51.2 | 49.9 | 49.4 | 49.7 | 42.8 | 42.0 | 39.5 | 37.8 | 36.1 | 36.8 | 36.2 | 35.7 | 37.2 |
| 2050 CSIRO Mk3.5 | Minimum | 57.6 | 56.1 | 53.6 | 51.1 | 49.3 | 50.3 | 49.3 | 48.9 | 48.5 | 41.9 | 40.5 | 38.5 | 36.5 | 35.5 | 36.3 | 36.1 | 35.7 | 35.8 |
| | Quartile 1 | 58.4 | 57.1 | 54.4 | 52.4 | 50.2 | 50.8 | 49.7 | 49.2 | 49.3 | 42.7 | 41.5 | 39.2 | 37.5 | 36.0 | 36.8 | 36.3 | 35.8 | 36.8 |
| | Median | 58.8 | 58.0 | 55.1 | 53.0 | 50.7 | 51.2 | 50.0 | 49.5 | 49.8 | 43.0 | 42.3 | 39.7 | 37.9 | 36.3 | 37.0 | 36.4 | 35.9 | 37.4 |
| | Quartile 2 | 59.0 | 58.7 | 55.5 | 53.8 | 51.4 | 51.7 | 50.3 | 49.6 | 50.4 | 43.2 | 42.9 | 40.1 | 38.5 | 36.7 | 37.3 | 36.5 | 36.1 | 38.0 |
| | Maximum | 59.2 | 59.2 | 57.0 | 55.1 | 52.3 | 52.5 | 50.7 | 50.0 | 51.0 | 43.5 | 43.4 | 41.3 | 39.5 | 37.4 | 37.7 | 36.7 | 36.3 | 39.0 |
| | Average | 58.7 | 57.9 | 55.0 | 53.0 | 50.8 | 51.3 | 50.0 | 49.5 | 49.8 | 42.9 | 42.2 | 39.7 | 38.0 | 36.3 | 37.0 | 36.4 | 36.0 | 37.4 |
| 2070 CSIRO Mk3.5 | Minimum | 57.8 | 56.2 | 53.7 | 51.3 | 49.7 | 50.3 | 49.5 | 49.0 | 48.6 | 42.1 | 40.6 | 38.6 | 36.8 | 35.8 | 36.5 | 36.3 | 35.9 | 36.0 |
| | Quartile 1 | 58.5 | 57.3 | 54.5 | 52.5 | 50.4 | 50.9 | 49.7 | 49.3 | 49.4 | 42.8 | 41.6 | 39.3 | 37.6 | 36.2 | 37.0 | 36.5 | 36.1 | 37.0 |
| | Median | 58.9 | 58.1 | 55.2 | 53.1 | 51.1 | 51.3 | 50.1 | 49.5 | 49.9 | 43.1 | 42.4 | 39.8 | 38.1 | 36.5 | 37.2 | 36.6 | 36.2 | 37.6 |
| | Quartile 2 | 59.2 | 58.9 | 55.7 | 53.9 | 51.6 | 51.8 | 50.4 | 49.8 | 50.5 | 43.4 | 43.0 | 40.2 | 38.6 | 36.9 | 37.5 | 36.7 | 36.3 | 38.3 |
| | Maximum | 59.4 | 59.3 | 57.1 | 55.1 | 52.4 | 52.5 | 50.8 | 50.1 | 51.1 | 43.6 | 43.5 | 41.5 | 39.7 | 37.6 | 37.9 | 36.9 | 36.5 | 39.2 |
| | Average | 58.8 | 58.0 | 55.2 | 53.1 | 51.0 | 51.4 | 50.1 | 49.6 | 49.9 | 43.1 | 42.3 | 39.8 | 38.1 | 36.6 | 37.2 | 36.6 | 36.2 | 37.6 |

†Wine regions: SD = Swan District, PH = Perth Hills, PL = Peel, GR-Geographe, MR = Margaret River, BW = Blackwood Valley, MJ = Manjimup, PM = Pemberton, GS = Great Southern

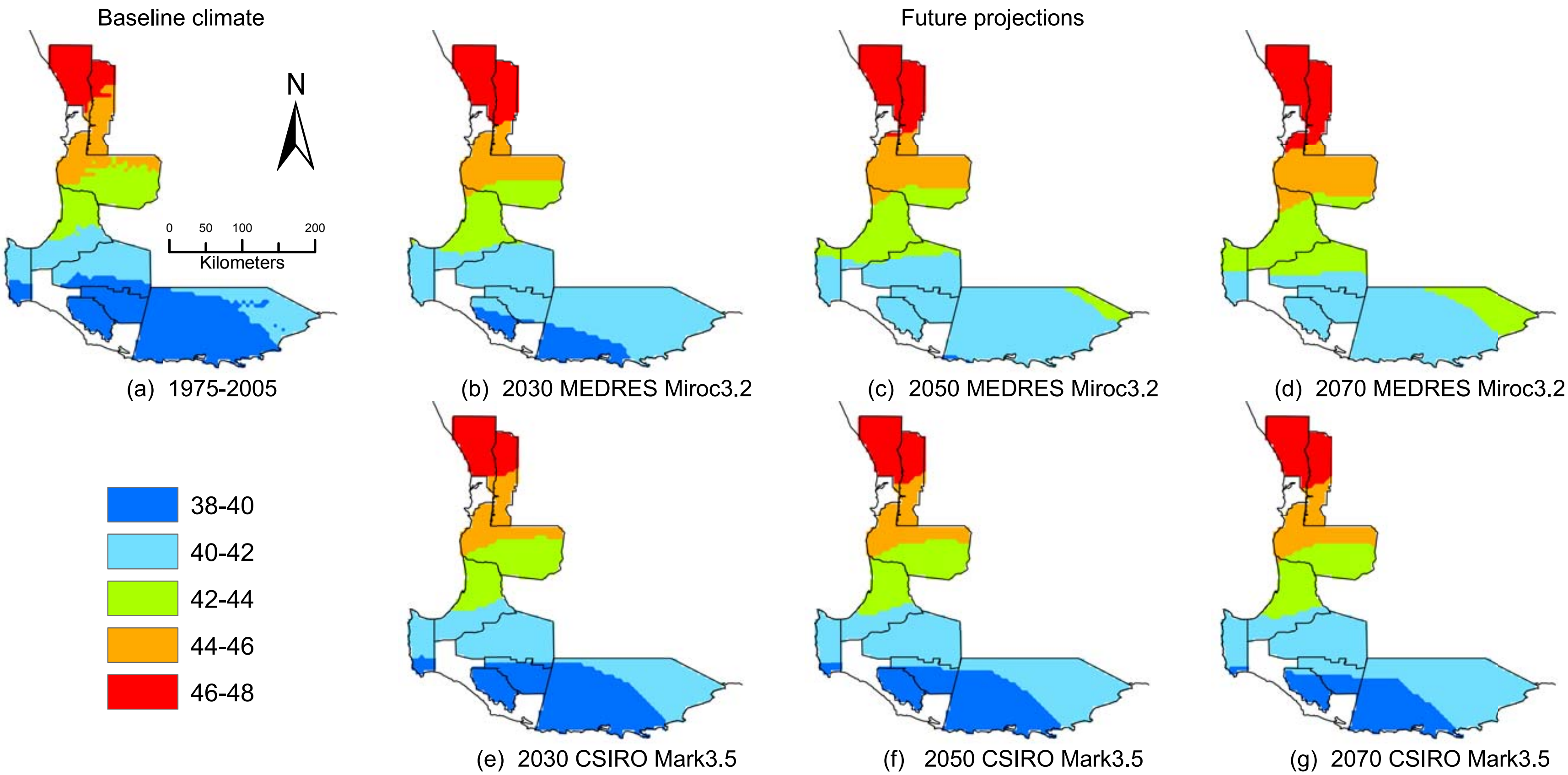


Figure 4.18 Current and projected total radiation during October to November (MJ/m$^2$) under SRES A2 emission scenario

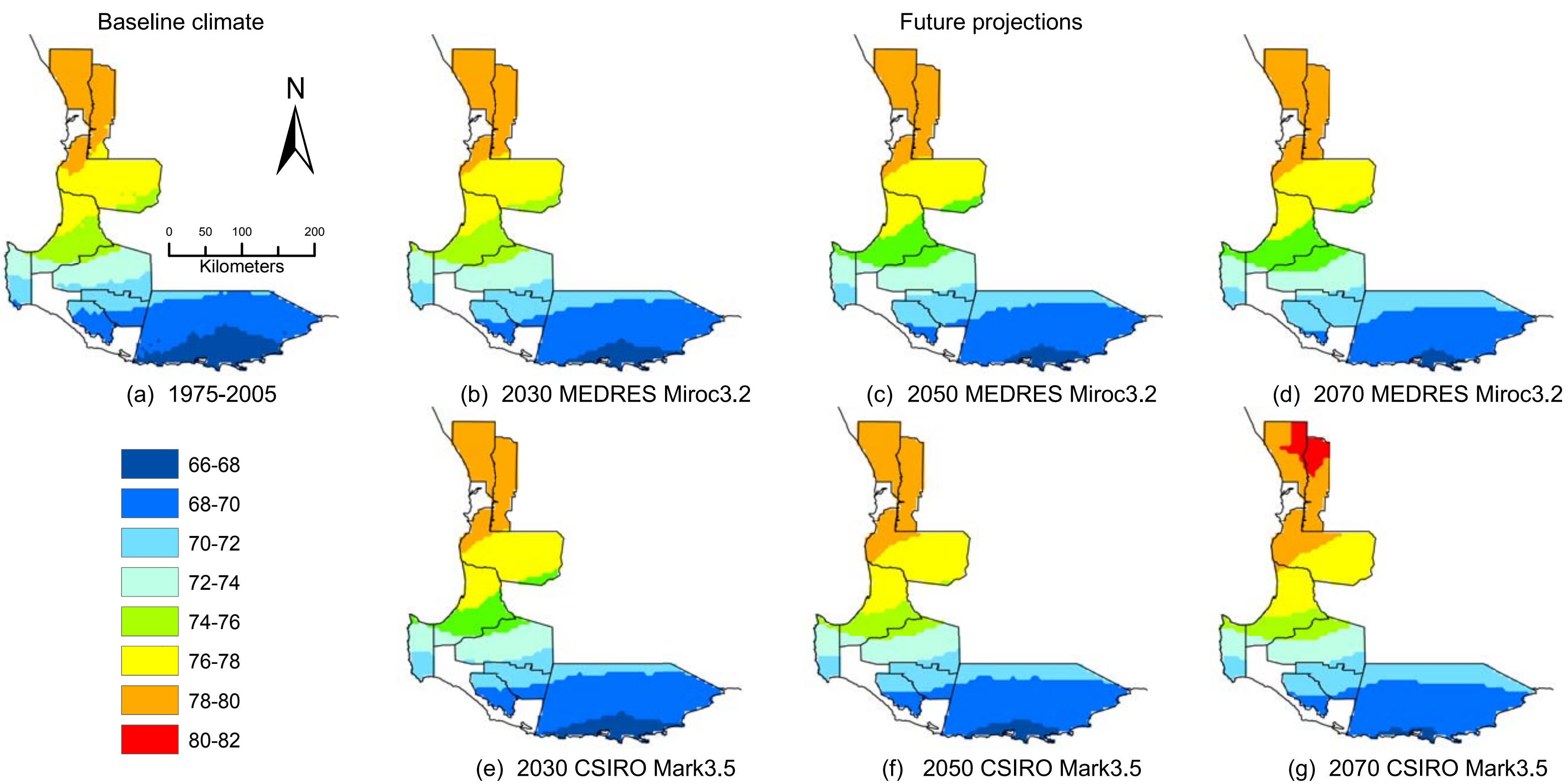


Figure 4.19 Current and projected total radiation during December to February (MJ/$m^2$) under SRES A2 emission scenario

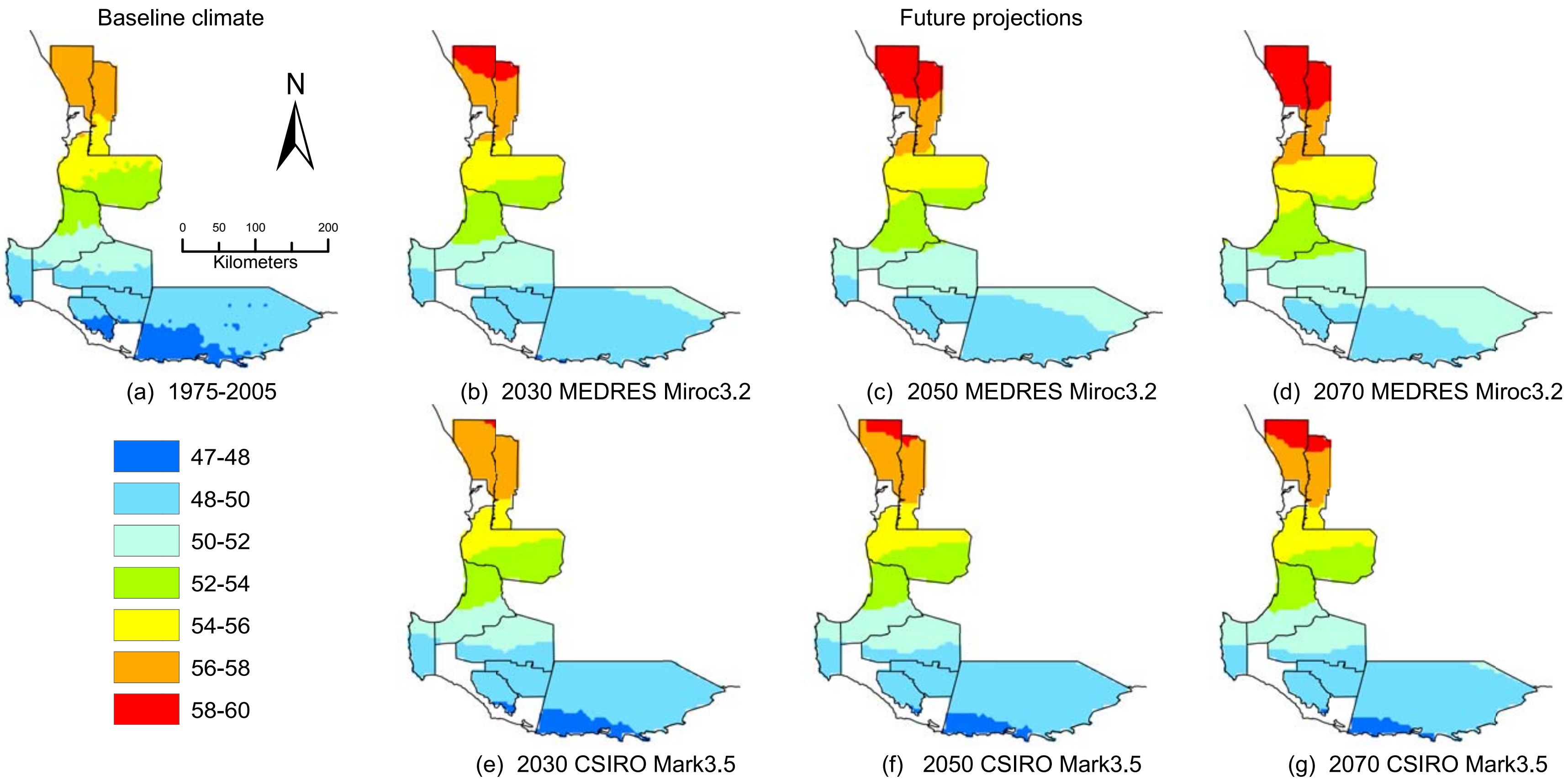


Figure 4.20. Current and projected total radiation during March to June ($MJ/m^2$) under SRES A2 emission scenario

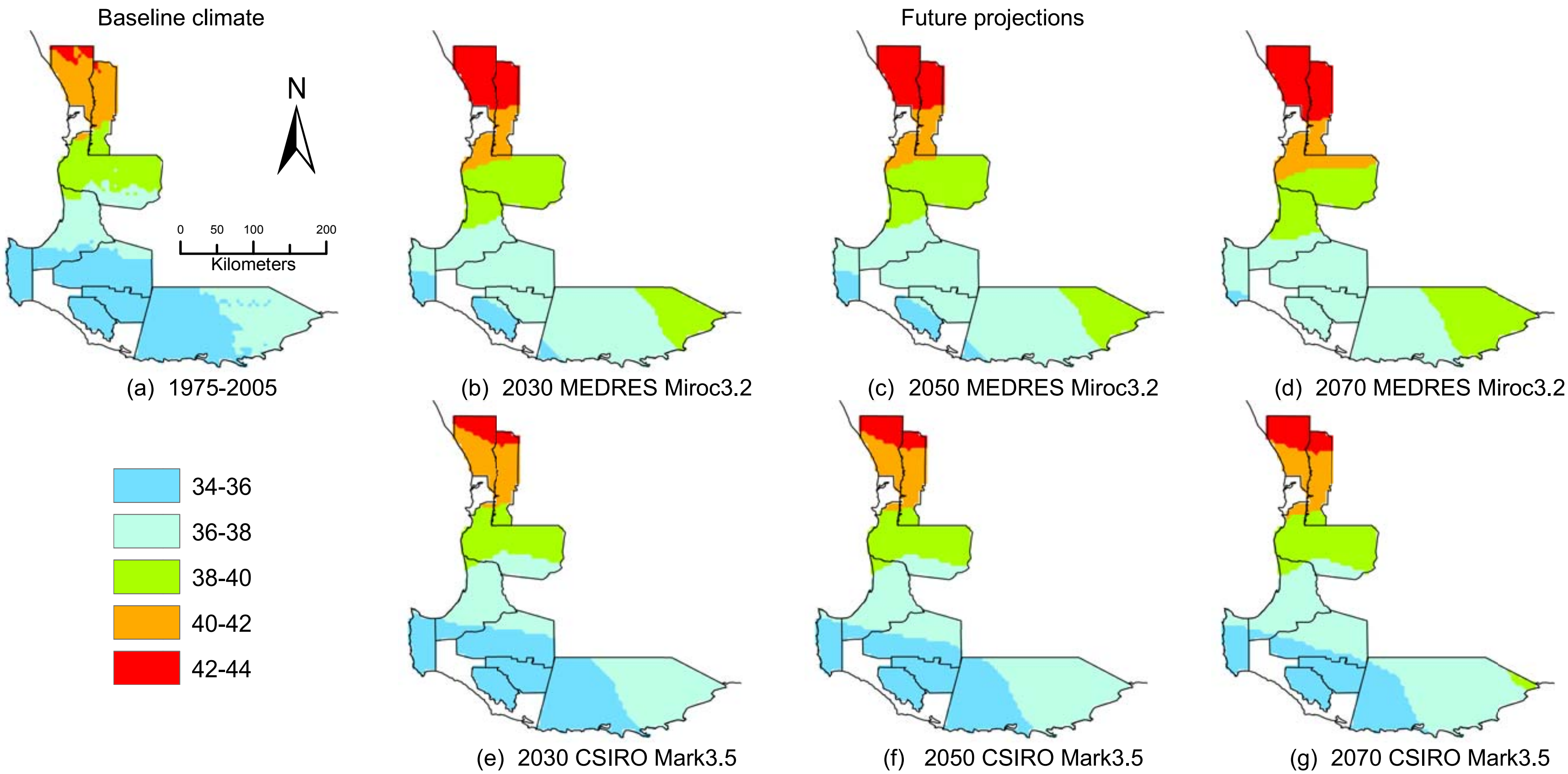


Figure 4.21 Current and projected total radiation during July to September ($MJ/m^2$) under SRES A2 emission scenario

## 4.4 Discussion

Like any other plant, the growth of winegrapes and the quality of grapes is effectively governed by climate parameters when other crucial factors such as nutrient availability are adequate (Kliewer, 1977, Coombe, 1987, Jackson and Lombard, 1993, Pearce and Coombe, 2004). Changes in the key climate indices have been projected for WA wine growing regions under future climate. Temperature based climate variables such as growing season average temperature, GDDs, and frequency of hot days are likely to increase. The projected decline in rainfall is substantial for some regions. Additionally, increases in the current spatial distribution of radiation levels are also projected, although the magnitudes of the increases are smaller.

The full actual impact of projected climate change is not easily quantifiable as the interaction of climate variables also plays an important role in winegrape growth, especially for grape quality attributes (Tarara et al., 2008). Potential impacts of key climate variables on viticultural regions in WA are discussed based in the light of past and present research.

### 4.4.1 Increases in average temperatures

Currently the warmest average GST is in the Swan District with 20.5 to 22°C, while it ranges between 17.5 to 19°C for the southern wine regions. Under climate change as much as a 1.5 to 4.5°C increase in average growing season temperatures has been projected across WA wine growing regions in the next 60 years under the SRES A2 emission scenario and depending on the climate models. A warming of such magnitude is likely to have significant impacts on existing winegrape physiology and grape composition across the wine regions.

As temperature is the main climatic driver of winegrape growth, the most obvious changes in the winegrape may be the advancement of phenological timing and the subsequent compaction of the growing season (Coombe, 1987, Pearce and Coombe, 2004, Webb et al., 2007). Nemani et al. (2001) reported an 18 to 24-day earlier start to the growing season in coastal

California between 1951 and 1997, coinciding with a 1.13°C increase in the annual average temperature. Jones and Davis (2000a) observed significant relationships between the increased number of hot days over 25 and 30°C during flowering and véraison resulting in earlier harvest dates during the second half of the last century in Bordeaux, even though the rate of increase in the number of hot days was small, only about 0.08 to 0.12 days per year. It also suggested that, depending on grape variety, a 12 to 30-day earlier vintage would occur if the average temperature increases by 2°C (Dry, 1988). Analogous to this, in the 1993 to 2006 period, the date for 21.8°Brix sugar maturity of Chardonnay, Shiraz, and Cabernet Sauvignon varieties was advanced between 0.5 to 3 days in Australian wine regions, and the likely causes of these changes were the increasing monthly average temperatures, rising at a rate of 0.19°C per year during this period (Petrie and Sadras, 2008).

The projected warmer GST is also likely to result in a shortened grape growing period. Webb et al. (2007) projected a 31 and 40-day shorter growing season for Cabernet Sauvignon and Chardonnay respectively, in the Margaret River region by 2050 when the projected growing season temperature is projected to be just over 2°C warmer compared to the 1990 baseline. Levels of grape quality components, such as sugars, phenolic compounds, and organic acids, increase or decrease during grape growth, especially during the ripening period and determine the overall grape quality at harvest (Coombe, 1987, Adams, 2006). The expected advancement of phenological development and the early maturity will potentially lead to diminished grape quality under hot climate conditions as has also been suggested by Webb et al. (2008a).

### 4.4.2 Potential effects of warmer conditions on grape quality

The average GST currently ranges between 17.5°C in southern regions to 22.0°C in the northern regions across the WA wine regions (Figure 4.2). Gladstones (1992) suggested that a ripening month average temperature between 15 to 21°C provides well balanced musts if the management is sound and the yield is moderate. In terms of heat units, lower values of

GDDs during October to April of 1500 units occur in the Great Southern region (Figure 4.7), which is within Region 2 of Winkler's classification of wine regions based on heat accumulation. In addition, the lower end of BEDD starts with 1500 units (Figure 4.8) which is well above the suggested BEDD ranges for most of the varieties making table wines (Gladstones, 1992). Therefore, at present WA regions are not limited by temperature or heat requirements, however any future increases will likely place them at the upper margin of viable premium wine production.

Grape maturity period (February to March) average temperature has been projected to increase. Environmental conditions during grape maturation have crucial effects on grape ripeness and berry quality attributes (Reynolds et al., 1995, Adams, 2006, Serrano Megías et al., 2006). From the point of view of plant physiology, an increase in temperature increases the rate of biochemical reactions (Devlin and Witham, 1983). A warmer and drier climate enhances the full maturity of grapes when the sunlight is adequate, however, the exact limits of the climate variables for optimum synthesis and accumulation of phenolic compounds are difficult to determine (Haselgrove et al., 2000, Bergqvist et al., 2001). What is obvious from viticultural practice and scientific research is that excessively high temperatures during grape ripening are detrimental for achieving optimum levels for quality wine making. For example, temperatures over 25°C decrease net photosynthesis and are ineffective for winegrape growth and for achieving balanced levels of fruit quality parameters (Kliewer and Torres, 1972, Gladstones, 1992). Grape berry size and weight are reduced when the temperature exceeds 30°C (Hale and Buttrose, 1974). The critical point here is that the rates of development of the different quality attributes are not uniform under different temperatures resulting in unbalanced grape quality attributes even when the grape reaches optimum sugar levels for wine making.

It is acknowledged that high quality wines are from environments with mild winters and low frost risk during spring resulting in uniform bud break as well as from those with low summer temperatures with less variability (Gladstones, 1992, Jones and Davis, 2000a, Nemani et al., 2001). Frost damage during spring and temperature variability during grape maturity are likely to be low for the WA wine regions (Figure 4.5 and 4.6), however, the impacts of increasing frequency of extreme hot conditions (Figure 4.9 and 4.10) are likely to be negative. It is known that extreme climate events such as prolonged hot spells cause reduced winegrape photosynthesis (Ferrini et al., 1995). Morondo and Bindi (2007) reported potential declines in yield and quality of Mediterranean crops, including winegrapes, due to the combined faster phenological development and the risk of more frequent extreme temperatures. It is also reported that extreme heat conditions could reduce the potential premium wine producing areas of the United States by over 80% by the end of this century (White et al., 2006).

Hot conditions also cause a decline in anthocyanin levels and potentially threaten grape quality (Chapter 3). It is well established that grape anthocyanin levels are reduced at higher temperatures beyond 30°C (Buttrose et al., 1971, Spayd et al., 2002, Tarara et al., 2008). This was starkly demonstrated by Mori et al. (2007) who showed more than 50% reduction in Cabernet Sauvignon anthocyanin concentration when exposed to a day time temperature of 35°C compared to exposure at 25°C. As reviewed by Jackson and Lombard (1993), grape anthocyanins are lessened or favoured when the night time temperature falls above or below 15°C, respectively.

Similarly, it is known that grape organic acids are decreased at high temperatures (Winkler, 1974, Jackson and Lombard, 1993). Negative relationships between warmer temperature and grape acidity are shown by the different titratable acidity levels on different sides of a vine row due to the temperature differences on those sides (Bergqvist et al., 2001). Low levels of total acidity are often related to higher levels of pH, both of which decrease grape and wine quality. The levels of organic acids in the grape berry is one of the key quality attributes responsible for maintaining fruit freshness, retaining flavour components, and contributing to the taste of wine (Mato et al., 2005, Conde et al., 2007, Sweetman et al., 2009). Projected warmer temperature will potentially affect overall grape quality through reduced acidity and potential increased pH levels, which are detrimental to wine aging and favourable to microbiological spoilage (Jackson and Lombard, 1993).

Negative impacts of high temperatures on grape quality are also borne out by different studies that used non-biological measures of grape and wine quality. Webb et al. (2008b) were able to demonstrate the negative relationships between the MJT and grape price paid by wineries in Australia. Based on the MJT and grape price relationships, it is further projected that a 7 to 39%, by 2030, and a 9 to 76%, by 2050, reduction in grape quality might occur on a national scale in Australia under climate change, if industry maintains current management strategies (Webb et al., 2008a). Temperatures during both January and the grape ripening period (30 days preceding harvest) correlate with vintage scores for Australian wine regions confirming the importance of temperature during this period on grape quality (Soar et al., 2008). According to Soar et al., (2008) maximum temperature below 28°C during early January were associated with better quality wines.

Increased temperature during ripening could also create additional pressure on wineries to spend extra resources. For instance, Webb et al. (2007) argued that warmer temperature during ripening period could cause problems with harvesting logistics, availability of a workforce and machinery due to the compressed vintage window, where all varieties, early and late need to be harvested within a shorter time interval. Moreover, the risk of loss of fruit quality potentially increases through oxidation when the grapes are crushed under hot conditions (Coombe, 1987, Haselgrove et al., 2000). These hot conditions could also lead to increased costs of refrigeration to control the must fermentation (Coombe, 1987). Decreased grape acidity, or increased pH levels might also require wineries to make acid additions to must or wine to improve the sensory characteristics and to improve the resistance to oxidation and microbial spoilage as already practised today in some warmer environments (Gladstones, 1992, Iland and Bruer, 2004). Unfavourable conditions and the associated costs required to deal with them may make them yet another impact of climate change on the WA wine industry.

### 4.4.3 Non-growing season average temperature

Most of the climate studies in the past have focused on climate effects on winegrape growth and berry quality composition during the grape growing season. The potential impacts of increasing off-season temperature on grape biology are unclear, despite the obvious impacts of the warming if the winegrapes are to be grown in cold environments where temperature is a limiting factor. However, one potential aspect of the off-season warming could be its effects on winegrape dormancy and abnormal bud break posing a potential risk for grape yield. Although the exact amount of chilling and temperature ranges are relatively unknown it is accepted that chilling is essential for terminating grape dormancy and providing uniform bud break (Lavee and May, 1997, Botelho et al., 2007). It is reported that chilling treatments at constant 10/4°C during day/night time temperatures resulted 3 weeks earlier 50% bud break of Riesling compared to same vines in 24/18°C day/night temperature environment during dormancy, indicating the importance of chilling (Schnabel and Wample, 1987). Warming off-season temperature will likely reduce the occasional risks of spring frosts across the study regions, but the warming might impact the dormancy and results in uneven bud break especially in Swan District, and coastal areas of Peel regions where the off-season average temperature are projected to reach 18.5°C from current 15.5°C (Figure 4.5).

### 4.4.4 Potential impacts of declining rainfall on Western Australian wine regions

The positive impacts of declining rainfall on winegrapes could be through decreased moisture conditions that retard fungal diseases or through water stress that enhances grape quality during grape maturity. However, these types of positive impacts may be irrelevant for WA wine regions, as the amount of current rainfall during the growing season is already low (Figure 4.17), and the vineyards rely on supplementary irrigation to reduce water stress.

Supplementary irrigation across the WA wine regions relies on rainfall harvesting mostly during winter as the most of the rainfall across the regions occurs during this period (Figure 4.16 and 4.17). Decreased soil water availability at the beginning of the winegrape growing season and decreasing rainfalls during the growing season potentially force growers to start irrigating earlier than normal, especially in the presence of simultaneous growing season temperature increases, and more frequent extreme hot days. If the water availability is less than the crop requirement, high temperature causes marked negative effects on grape physiological processes due to the progressive heating of the plant (Galo et al., 1996). However, it is acknowledged that a full assessment of decreasing rainfall impacts on winegrapes requires consideration of other factors such as soil water balances at the beginning and during the growing season, and the effects of elevated $CO_2$ for vine growth.

### 4.4.5 Changes in radiation

The most detectable shifts in radiation levels were projected to happen during the winter period indicating a minimal direct impact on photosynthesis and grape quality. The projected increases in winter radiations (up to 2 $MJ/m^2$) across the regions (Figure 4.21) may elevate evaporation, and the combined impact of declining rainfall and increased evaporation will likely be through decreased soil moisture and harvested water reserves at the beginning of the growing season. Nevertheless, the magnitude of the change in the projected radiation indices were small, with a maximum potential 5.8% increase by 2070 only in the Great Southern region during the July to September period. In addition, the projected maximum increase in radiation is at least 4 to 8 times less than the natural radiation gradient between the northern and the southern districts, suggesting minimal radiation impact on the wine regions in this study.

## 4.5 Conclusion

The current grape growing climate niches of all the WA wine regions are likely to be changed in coming decades. Accumulation of heat units and temperatures of the grape growing season and grape maturity period are projected to increase considerably, which in turn will likely impact wine production across the regions. The anticipated decreases in rainfall and increased temperature during the grape growing season might cause significant changes in future irrigation demand. For example, decreased winter and spring rainfall together with increased temperatures might require an earlier start to irrigation and lead to a shortage in water availability during critical periods later in the growing season. This would be a critical impact given that the Great Southern region faces water shortage issues even under the current climate. A water balance study would be recommended to evaluate the impacts of the combined effects of decreasing rainfall and increasing temperature.

The projected warmings in the climate indices in this study are higher than what has been observed in winegrowing regions around the world in the past decades, on which some discussion has been based. Therefore, the potential impacts of the projected climate change on some WA wine regions will likely be much greater than what has been experienced so far.

# CHAPTER 5. MODELLED GRAPE QUALITY ATTRIBUTES UNDER CLIMATE CHANGE IN WESTERN AUSTRALIAN WINE REGIONS

## 5.1 Introduction

Despite our continually advancing knowledge in management practices to manipulate and control grape growth and development, viticulture remains a highly vulnerable sector to climate change due to the narrow climate niche for producing premium quality grapes and wines. Past research relating to climate change impacts on viticulture projected significant impacts. Perceived impacts include, but are not limited to: winegrape growth and phenology (Jones and Davis, 2000b, Hayhoe et al., 2004, Webb, 2006, Webb et al., 2007, Caffarra and Eccel, 2011), grape yield (Bindi et al., 1996, Lobell et al., 2006), grape and wine quality (Jones et al., 2005, Webb et al., 2008a) and disease pressure (Chakraborty et al., 1998, Salinari et al., 2007).

White et al. (2006) suggested that the premium wine growing regions of the United States would decline by more than half by end of this century due to increases in extreme hot days, and also speculated that increased temperature and heat accumulation would force wine production to shift to varieties suited to warmer climates to avoid low quality wines. Bindi et al. (1996) also warned about elevated yield variability under climate change due to the increased $CO_2$ concentration which might imply increased economic risk to grape growers.

Based on relationships between wine quality and growing season temperatures, Jones et al. (2005) predicted uneven impacts of climate change on wine quality across regions depending on the current climate and the magnitude of future warming. Webb et al. (2008a) have also argued that there is likely to be variation in the sensitivity to climate change among winegrape varieties, but that without adaptive measures winegrape quality in Australia will generally decrease. Hall and Jones (2009) also concluded that wine quality is likely decrease in Australia due to an increased number of wine growing regions with unsuitable growing season temperature for premium wine production under climate change.

The findings of the above studies indicate the possible direction of climate change impacts on winegrape phenology and grape and wine quality. However, grape and wine quality is a subjective concept; there is no single measurable parameter that defines the quality objectively as a whole. Consequently, studies to date have utilized vintage or wine ratings as surrogate measures of grape or wine quality. For example, Jones and Davis (2000a), Nemani et al., (2001), Jones et al. (2005), Storchmann (2005), and Sadras et al. (2007a) all used vintage ratings (in one or another format) as a wine quality indicator and linked it to climate variables. Webb et al. (2008a) identified grape price as an alternative grape quality as a surrogate in Australian conditions and used it for climate change impact study. Similarly, historical wine prices and climate variable relationships were also investigated to predict wine quality in Bordeaux (Ashenfelter, 2008).

Grape colour, acidity, and pH are considered as key parameters of grape quality (Francis and Newton, 2005), and levels of these attributes play an important role for final wine quality. However, potential impacts of climate change on these grape quality attributes have not been quantitatively evaluated. Objectives of this study were to evaluate potential impacts of future climate change on key grape quality attributes; anthocyanin concentrations, titratable acidity (TA), and pH of Cabernet Sauvignon, Shiraz and Chardonnay, which are the most common winegrape varieties for the Western Australian (WA) wine regions.

This study differentiates itself from other climate change impact studies for viticulture by using empirical models, which were developed from measured grape quality and climate data across different vineyards located along a 700 km natural climate gradient transect (see Chapter 3). Grape quality surfaces have been constructed utilizing downscaled (~5 km) outputs of two global climate models (GCM) that project the lowest and the highest warming for Western Australian wine regions (see Chapter 4 for more details). The fine resolution climate model outputs made it possible to examine inter, and intra regional differences of grape quality attribute changes under future climate.

## 5.2 Materials and methods

### 5.2.1 Study regions

Description and locations of the Western Australian wine regions have been given in Chapter 4 (Figure 4.1 of Chapter 4). These regions have distinguishable environmental characteristics differing from each other, and are listed in the Australian Geographic Indications which legally differentiate Australian wine growing areas based on the wine quality characteristics and reputation that are attributable to the geographical regions (Wine Australia, 2011). This study refers the Swan District, Perth Hills, and Peel regions as the northern; Geographe, Margaret River, and Blackwood Valley regions as central; and the Great Southern, Pemberton, and Manjimup regions as the southern regions throughout this chapter.

### 5.2.2 Grape quality model development

Grape quality attribute model development, and selections have been introduced and discussed in Chapter 3.

The grape quality models have been developed at a common (total soluble solids (TSS) of 22 °Brix) grape maturity utilizing measured grape quality attributes (anthocyanin, TA, and pH for Cabernet Sauvignon, Shiraz, and Chardonnay varieties) and a comprehensive range of climate variables (See Chapter 3 for detailed descriptions). Climate variables used for the grape quality models were calculated from downscaled daily minimum and maximum temperatures, rainfall, vapour pressure deficit, and radiation values under current and projected climate. Impacts and biological relevancies of these climate variables to winegrape were discussed in Chapter 3. Some quality attributes had several candidate models (Chapter 3), however, for this study we focused on models (Table 5.1) whose outputs are compatible with the observed grape quality attributes across the study regions, and consistent in their predictions in the future. All other projected surfaces for grape quality attributes are shown in Appendix 2.

Table 5.1 Model estimates for berry juice anthocyanins (mg/g) concentrations, titratable acidity (g/L) and pH at common maturity (total soluble solid of 22 °Brix)

| Quality attributes | Variety | Intercept | Climate variable | | | | | | | | | Performance | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | VPD_Oct | GDD_GS† | DR_OF | DR_Feb | DR_GS | RN_GS | Tav_Jan | $T_{mn}$_RP‡ | Rad_Oct | Adj_$R^2$ | $VIF_{max}$ |
| Anthocyanin | Cabernet Sauvignon | 3.63 | | | | | | | -0.094** | | | 0.65 | |
| | Shiraz | 2.59 | | | | | | | -0.051 | | | 0.77 | |
| TA | Cabernet Sauvignon | 19.2 | | | | | -0.003 | | | -0.389 | | 0.77 | 1.20 |
| | Chardonnay | 16.11 | | | | -0.030 | | | | -0.935 | 0.942** | 0.82 | 2.35 |
| | Shiraz | 13.34 | | | -0.003 ** | | | 0.009** | | | | 0.82 | 1.48 |
| pH | For all three varieties | 2.06 | 0.002 | 0.001 | | | | | | | | 0.52 | 1.31 |

This table is subset of Table 3.4 to 3.6 in Chapter 3. Standard errors and Confidence Intervals for the parameter estimates are given in Table 3.4 to 3.6. Significance; all significant at <0.001 level, except marked as * $p < 0.05$, and ** $p < 0.01$. †Growing season refers to the period between October to a day when grape maturity reaches a total soluble solid of 22 °Brix, ‡Ripening period = 30 days preceding the 22 °Brix maturity, VPD_Oct = vapour pressure deficit for October (kPa), GDD_GS = growing season Growing degree days, DR_OF, DR_Feb , and DR_GS = diurnal ranges for, respectively, October to February, February, and Growing season, RN_GS = growing season rainfall (mm), Tav_Jan, and Tav_RP = average temperature for January, and Ripening period (°C), Tmn_RP=minimum temperature for ripening period (°C), Rad_Oct = October mean radiation (MJ/$m^2$)

### 5.2.3 Projection of grape maturity dates

The modelling work presented in Chapter 3 has shown that some grape quality attributes were influenced by climate variables during periods preceding an actual maturity date. In particular, climate variables during the grape growing season (GS), i.e. between 1st of October and the date when the fruit reaches the common maturity, and ripening period (RP), i.e. 30 days preceding the common maturity, were influential for some grape quality attributes. Further, the lengths of GS and RP varied with varieties (Chapter 3). Therefore, future maturity dates specific to each variety were required in order to calculate values of climate variables for GS and RP. It is acknowledged that (1) there are variations in the actual start date of vine growth across regions and years depending on weather, and (2) the actual grape harvest does not necessarily occur at the TSS of 22 ºBrix as used as harvest maturity in this study. However, for modelling simplicity, we used the above terms for defining the GS and RP for this study.

Two different methods were employed to model grape maturity dates. The first approach was based on the accumulative Biologically Effective Degree Day (BEDD) index conceived by Gladstones (1992). The BEDD uses the same principle as the growing degree day concept by Winkler (1974), but with additional adjustments (see Chapter 4 for more detail). According to this

BEDD concept to reach maturity Cabernet Sauvignon, Shiraz, and Chardonnay varieties require, respectively, 1300, 1250, and 1150 units of BEDD accumulation starting from the 1st of October (Gladstones, 1992). Thus, for this study, the respective number of BEDDs for the above varieties were calculated between 1st of October and the date on which the required amount of heat accumulation is reached; the results were spatially analysed across the regions under current climate regime for comparison with the modelled maturity dates by the second approach of this study.

The second approach for determining the grape maturity date was based on empirically derived climate and plant growth relationships. However, in this instance an extensive maturity date model searching analysis was carried out using measured grape and climate data. This process followed the same procedure and criteria as described in Chapter 3 for the grape quality modelling section, but with the aim of finding the best potential climate variables that adequately determine the days on which a winegrape variety reaches the common maturity.

An ideal method to test the maturity date model performance would be to examine how they reproduce historical harvest dates. However, for this study we did not have sufficient data to carry out this type of analysis across the study regions. In addition, the first approach was not specifically designed for predicting grape maturity at a definite ripening stage, whereas, the second approach used historical data at a defined maturity of 22 °Brix TSS. From experience, it is known that the actual grape harvest does not occur at the same sugar level that is used here, rather it is mainly at the discretion of winemakers depending on the intended wine styles. Therefore , it was not suitable to assess the maturity date model performances using a one-on-one basis. Instead, we subjectively assessed the model performances. To do so, maturity dates of Cabernet Sauvignon, Shiraz, and Chardonnay varieties were reproduced by both approaches using current climate data (i.e. average of the 1975-2005 period) and compared them for their comprehensiveness. The main criterion used for this comparison was whether the variations of the modelled maturity dates of the varieties conform with the expert knowledge on the maturity dates of the varieties across the regions taking the known climate variations across the regions into considerations.

### 5.2.4 Future climate and its uncertainties

Selections of emission scenarios, GCMs and downscaling techniques have been described in detail in Chapter 4. Consistent with Chapter 4, the low and high warming climate change ranges correspond to projections with the MEDRES Miroc 3.2 model with low representative warming, and the CSIRO Mk3.5 model with high representative warming range. These low and high warming ranges encompass future temperature uncertainties in WA wine regions under SRES A2 emission scenario.

### 5.2.5 Construction of grape quality attribute surfaces

Potential impacts of climate change on grape quality attributes were projected by driving the empirical regression models by the current and the projected future climates for the years 2030, 2050, and 2070. Current and future climates were defined here as an average of 31 years of climate data centred at the nominated year. Surfaces of the influential climate variables for grape quality attributes were constructed and screened under current and future climate conditions before these were applied to the grape quality models. Construction of grape quality surfaces using the multiple regression models is illustrated in Figure 5.1 using the Cabernet Sauvignon TA surface development as an example. All other influential climate variables used for modelling the grape quality attributes are shown in Appendix 3.

### 5.2.6 Spatial analysis

All modelling and spatial analysis of the potential grape fruit quality surfaces for current and future climate were carried out with the Geographic Information System (GIS) package ArcGIS 9.3 (ESRI, Redlands, CA). The following steps were followed: firstly, the Western Australian wine region feature maps were created in ArcGIS by digitising existing hard copy maps, which were in accordance with the descriptions of Geographic Indications

(GI) of Australian wine regions and labelled (Chapter 4). Secondly, relevant surfaces of the climate variables, which were used for the grape quality attribute models were constructed from the modelled climate data. A total of 20 climate surfaces covering the regions of this study were created and georeferenced. Thirdly, the grape quality attribute surfaces were created by driving the climate surfaces by the relevant model parameter estimates from the quality models (see Figure 5.1 for illustration). Finally, the grape quality surfaces were extracted within the WA GI boundaries and relevant statistics were derived from values of the raster pixels whose centroid is located within wine region boundaries. All grape quality raster maps were then reclassified for spatial analysis. These processes were repeated for current and future climate conditions to analyse grape quality changes over temporal and spatial dimensions with the two GCMs that project low and high warming conditions across the study wine regions.

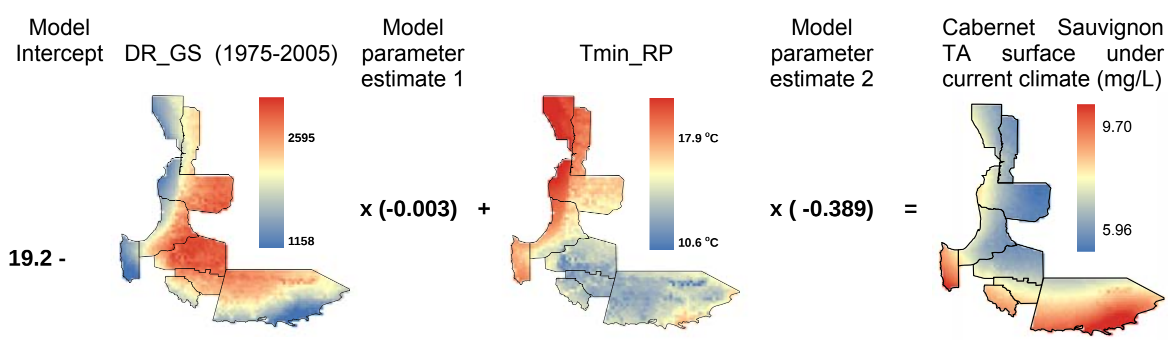


Figure 5.1 Illustration of grape quality attribute modelling. Above climate variables (see Table 5.1) were used for constructing Cabernet Sauvignon titratable acidity levels at 22 °Brix total soluble solid maturity under current climate. DR_GS=Diurnal range during Cabernet Sauvignon growing season, Tmn_RP= average minimum temperature during Cabernet Sauvignon ripening period. This process is repeated for different time intervals using projected climate data

## 5.3 Results

### 5.3.1 Maturity date modelling results

The best regression models for maturity dates across varieties were different among varieties. For example, the mean daily maximum temperature in November and total radiation between December and February jointly explained as much as 94% of the variation in Cabernet Sauvignon maturity date. For Chardonnay, about 93% of the maturity date variations were accounted for by rainfall during September to November, and the average temperature between October and February. On the other hand, the mean minimum temperature in February was the most influential variable for Shiraz maturity, accounting for 82% of its variation. Relationships between the above variables and maturity were consistent with known effects, such as hastened growth and ripening under warmer temperature (Jackson and Lombard, 1993, Freeman et al., 1980), while rainfall during the earlier season possibly led to late maturity through increased soil water availability, which is known to be positively correlated with increased vegetative growth (Koundouras et al., 2006).

However, for this study, grape maturity models with temperature components during the growing season were favoured as it is well known that temperature is the main driver of plant growth rate when other factors are constant. Regression models with average temperature (natural-log scale) between October and February period explained 94%, 92%, and 88% of Cabernet Sauvignon, Shiraz, and Chardonnay maturity date variations, respectively (Table 5.2). Effects of October to February period average temperature were consistent across varieties, thus these simple regression models have been examined further for comparison with the BEDD based approach.

When examined under the current climate condition (averaged for the 1975 to 2005 period), predictions of grape maturity dates by BEDD accumulation, and the regression approach show noticeable differences. For example, when constructed by the BEDD approach, Cabernet Sauvignon and Shiraz varieties fell into four groups (each contains 10 days intervals) starting from 20 February and ending 30 March, across the entire wine regions of Western Australia (Figures 5.2 and 5.3). Similarly, with this approach, Chardonnay maturity started about 10 February, but ended in within one month across the regions (Figure 5.4).

Table 5.2 Grape maturity and October to February average temperature relationships

| Variety | Relationships | Model coefficients and standard errors (in bracket) | | | | |
|---|---|---|---|---|---|---|
| | | *a* | | *B* | | *Adj_R2* |
| Cabernet Sauvignon | $y = a*x^b$ | 62.55** | (11.63) | -2.49*** | (0.17) | 0.94 |
| Shiraz | $y = a*x^b$ | 79.58* | (22.6) | -2.721** | (0.26) | 0.92 |
| Chardonnay | y = a*x + b | -5.39*** | (0.53) | 19.85** | (1.56) | 0.88 |

*y*- day of year, *x*-October to February average temperature (°C) , Significance; *p<0.01, **p<0.001. standard errors are in parentheses. Both y and x are in natural log-scale.

Estimating maturity dates with the regression approach produced elaborate patterns. For example, Cabernet Sauvignon and Shiraz varieties reached the common maturity about 10 February in the warmer Swan region, but in cooler southern regions the same levels of maturity were attained around the middle of April (Figures 5.2 and 5.3). A few elevated places in the mountainous Stirling range indicate much later Cabernet Sauvignon and Shiraz maturities extending to the beginning of May (Figure 5.3). With this modelled approach, Chardonnay reached the common maturity in late January in the northern regions, but it took more than 2 months additional time to reach the same maturity in the cooler southern regions (Figure 5.4). Modelled grape maturity dates, as a function of October to February average temperature, revealed more detailed grape maturity patterns that reflect temperature and grape growth relationships across the regions, than the maturity dates based on BEDD accumulation. Therefore, this regression approach was preferred to the BEDD based approach and was used for projecting future grape maturities. Climate variables for growing seasons (or ripening periods) that were specific to different grape varieties were then recalculated from the modelled maturity dates.

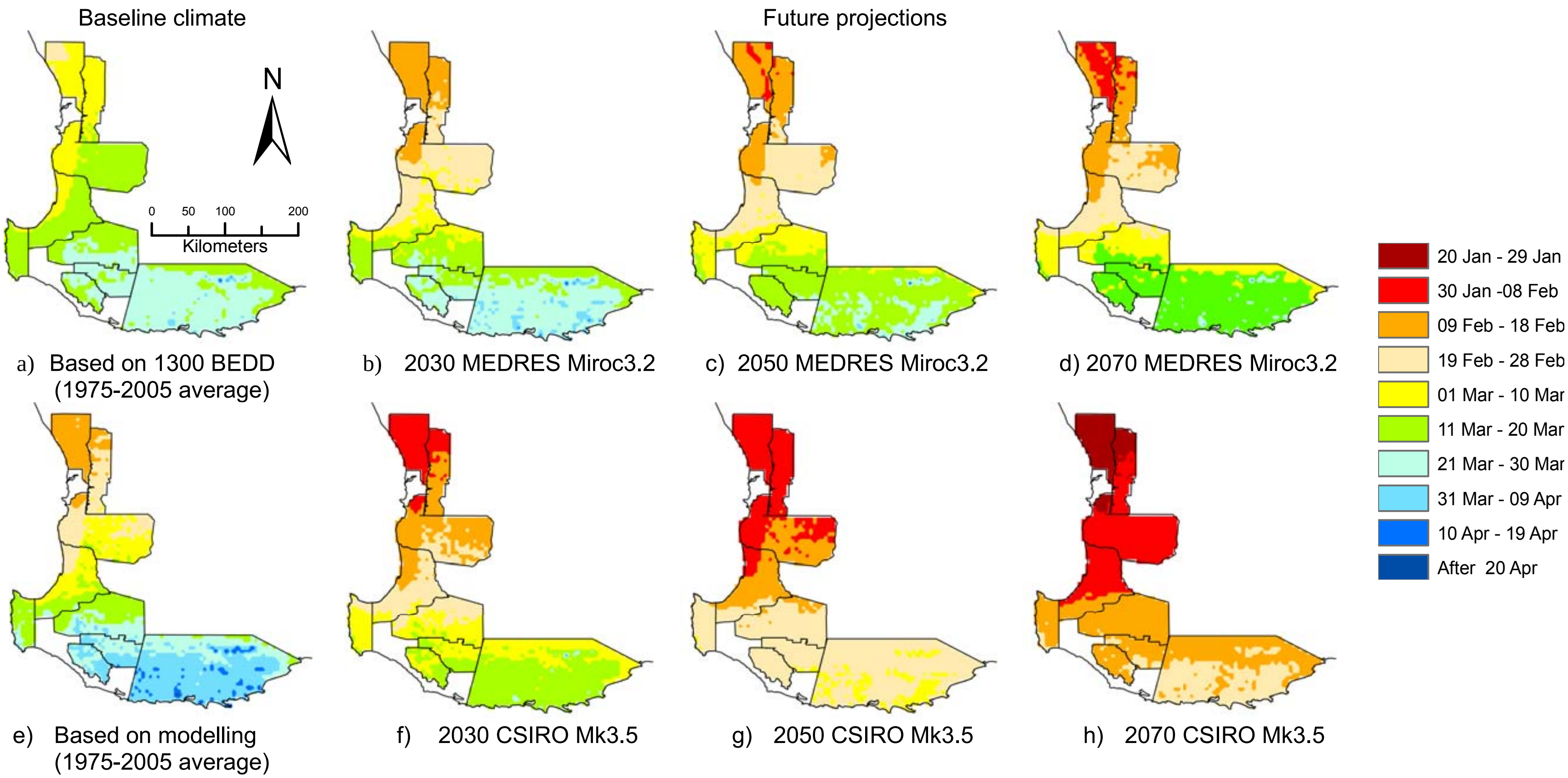


Figure 5.2 Modelled current and future Cabernet Sauvignon maturity dates. (a) Maturity dates based on 1300 biologically effective degree days under current climate. (b) to (h) Modelled maturity dates at 22 °Brix Total soluble solid maturity based on regression model with October to February average temperature under SRES A2 emission scenario

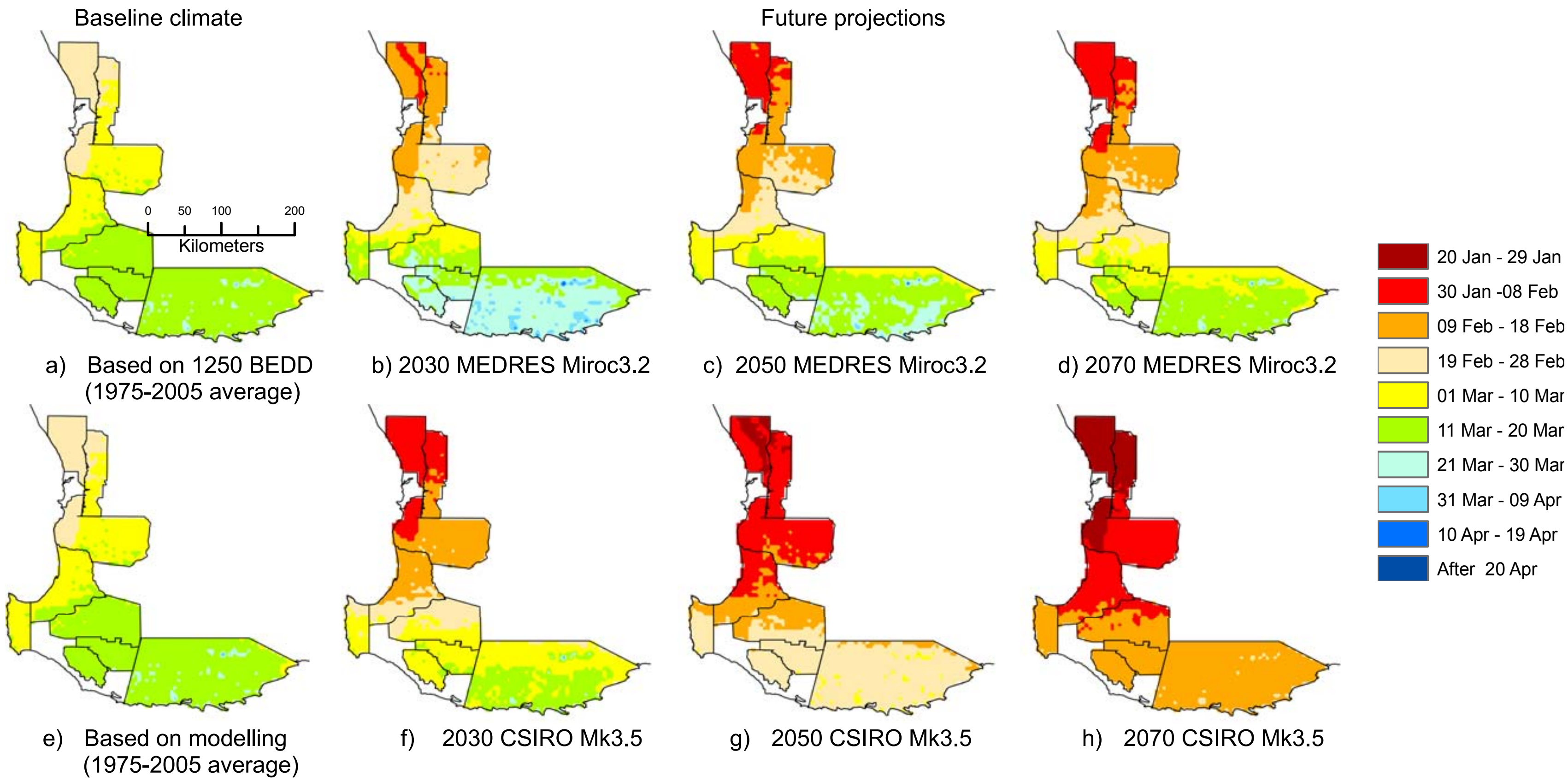


Figure 5.3 Modelled current and future Shiraz maturity dates. (a) Maturity dates based on 1250 biologically effective degree days under current climate.

(b) to (h) Modelled maturity dates at 22 °Brix Total soluble solid maturity based on regression model with October to February average temperature under SRES A2 emission scenario

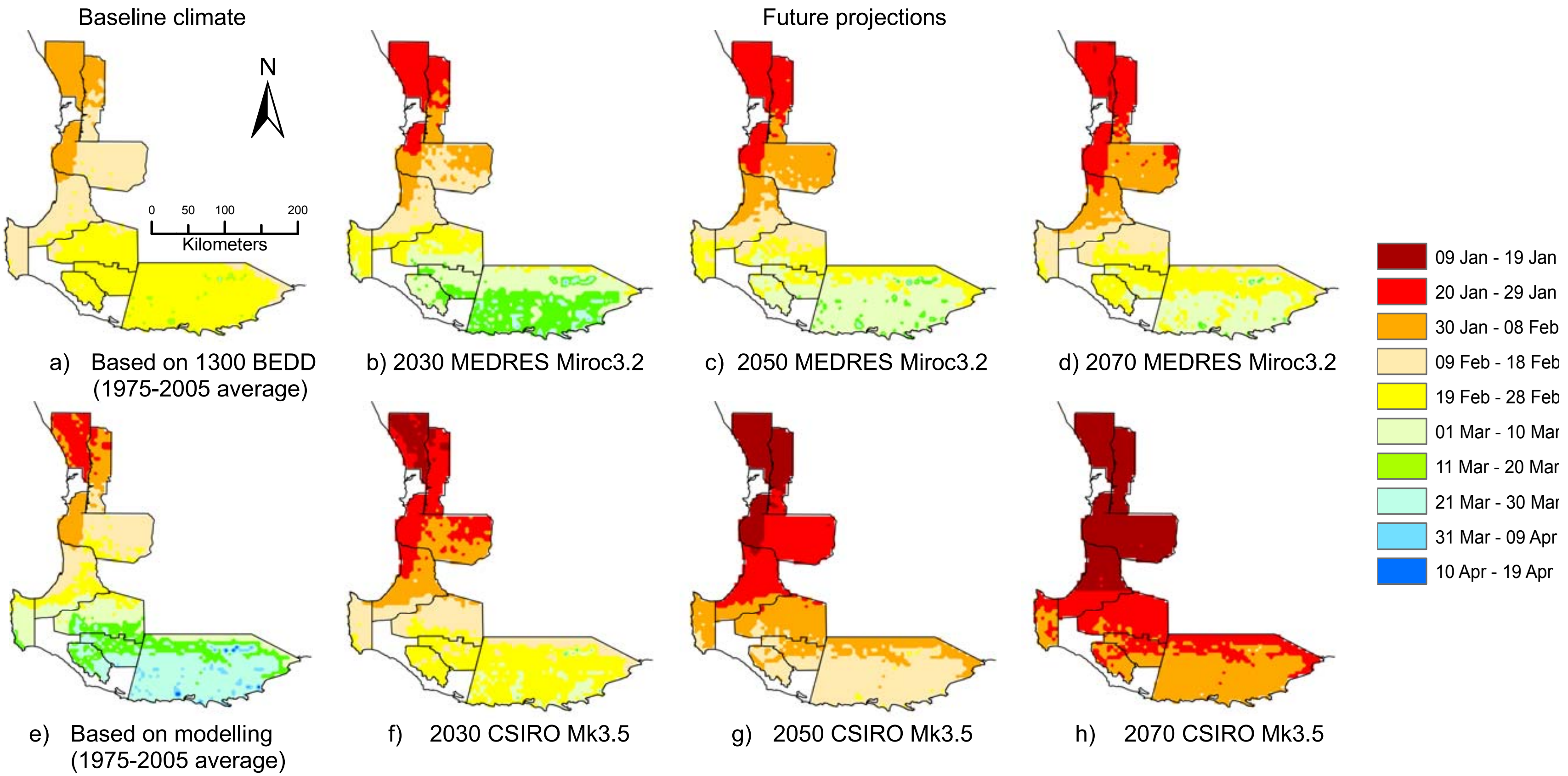


Figure 5.4 Modelled current and future Chardonnay maturity dates. (a) Maturity dates based on 1150 biologically effective degree days under current climate. (b) to (h) Modelled maturity dates at 22 °Brix Total soluble solid maturity based on regression model with October to February average temperature under SRES A2 emission scenario

## 5.3.2 Projected grape maturity under climate change

Impacts of climate change on grape maturity are likely to be more pronounced in the southern wine regions under both low and high warming scenarios. By 2070, under high warming climate change scenario, Cabernet Sauvignon and Shiraz varieties are projected to reach the common maturity 6 weeks early in the southern wine regions compared to current maturity dates, while Chardonnay maturity will potentially be about 7 weeks earlier than the current dates (Figure 5.5). On the other hand, the same varieties might reach the same common maturity about only 19 to 20 days earlier in the warmer northern regions compared to the current climate conditions indicating uneven advancement of grape maturities across the regions under climate change (Figures 5.2 to 5.5). Under low warming climate scenario, the above three varieties are projected to reach the same common maturity about a week earlier by 2070 in warmer districts, while in cooler southern regions, for example, in the Great Southern region it is projected to be about 18, 20, and 22 days earlier, respectively, for Cabernet Sauvignon, Shiraz , and Chardonnay (Figures 5.2 to 5.5).

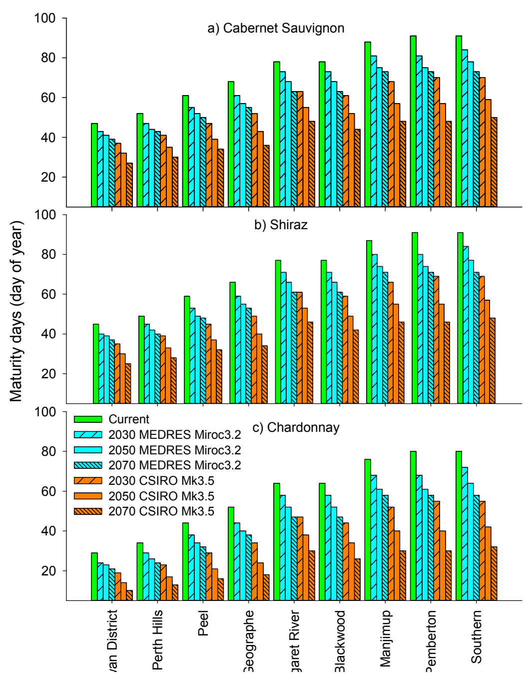


Figure 5.5 Modelled median grape maturity days at common maturity (total soluble solids of 22 °Brix) under current and projected future climate. MEDRES Miroc3.2 and CSIRO Mk3.5 models represent low and high warming climate assumptions across the wine regions under SRES A2 emission scenario

### 5.3.3 Grape quality attributes under climate change

#### 5.3.3.1 Projected anthocyanin concentrations under climate change

Compared to their 1990 level, Cabernet Sauvignon median anthocyanin concentrations are projected to decrease unevenly across the regions, but progressively with time. Under high warming scenario, median anthocyanin concentrations are projected to decrease up to 33% in the northern districts (for example, current 1.34 mg/g per fresh weight median anthocyanin concentrations drop 0.90 mg/g in Swan District), while 18% reductions are projected for the southern regions by 2070 (Table 5.3). Impacts of low warming climate change on Cabernet Sauvignon anthocyanins concentrations at maturity will likely be spatially similar, but the magnitude is projected to be 3 to 4 times less than that of high warming (Table 5.3).

The maximum decrease in the Shiraz anthocyanin concentrations is projected to be 18% for the Swan District under high warming range compared to concentrations under 1990 average climate. This reduction gets smaller towards the cooler regions in the south reaching a 9% decrease in the Margaret River by 2070. The biggest decline of Shiraz anthocyanin concentrations under low warming climate change range is projected to be between 3 to 4% by 2070 across the wine regions (Table 5.3).

Spatial analyses of the anthocyanin concentrations surfaces indicate that changes in future anthocyanin concentrations are caused by southward shifting of current potential anthocyanin concentrations that is driven by the changes in projected climate (Figure 5.6 and 5.7). When high warming range is assumed, current concentrations of Cabernet Sauvignon and Shiraz anthocyanins, will likely be similar to anthocyanin concentrations that currently exist in adjacent warmer areas to the north by 2030 (Figures 5.6 and 5.7).

Table 5.3 Current and projected median Anthocyanin concentrations (mg/g) at common maturity (total soluble solid of 22 °Brix) across Western Australian wine regions under SRES A2 emission scenario

| Variety | Time and warming ranges[†] | | Swan District | Perth Hills | Peel | Geographe | Margaret River | Blackwood | Manjimup | Pemberton | Great Southern |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Wine regions | | | | | | | | |
| Cabernet | Current | | 1.34 | 1.37 | 1.46 | 1.54 | 1.71 | 1.64 | 1.72 | 1.76 | 1.78 |
| Sauvignon | 2030 | 1 | 1.30 | 1.33 | 1.42 | 1.51 | 1.68 | 1.60 | 1.69 | 1.73 | 1.75 |
| | | 2 | 1.18 | 1.22 | 1.32 | 1.40 | 1.62 | 1.52 | 1.61 | 1.64 | 1.67 |
| | 2050 | 1 | 1.26 | 1.29 | 1.38 | 1.47 | 1.64 | 1.57 | 1.65 | 1.69 | 1.71 |
| | | 2 | 1.05 | 1.10 | 1.19 | 1.28 | 1.54 | 1.42 | 1.51 | 1.54 | 1.57 |
| | 2070 | 1 | 1.23 | 1.26 | 1.35 | 1.44 | 1.62 | 1.54 | 1.63 | 1.67 | 1.68 |
| | | 2 | 0.90 | 0.97 | 1.06 | 1.14 | 1.45 | 1.31 | 1.40 | 1.44 | 1.46 |
| Shiraz | Current | | 1.35 | 1.36 | 1.41 | 1.46 | 1.55 | 1.51 | 1.55 | 1.57 | 1.59 |
| | 2030 | 1 | 1.33 | 1.34 | 1.39 | 1.44 | 1.53 | 1.49 | 1.54 | 1.56 | 1.57 |
| | | 2 | 1.26 | 1.29 | 1.34 | 1.38 | 1.50 | 1.45 | 1.49 | 1.51 | 1.53 |
| | 2050 | 1 | 1.30 | 1.32 | 1.37 | 1.42 | 1.51 | 1.47 | 1.52 | 1.54 | 1.55 |
| | | 2 | 1.19 | 1.22 | 1.27 | 1.31 | 1.45 | 1.39 | 1.44 | 1.46 | 1.47 |
| | 2070 | 1 | 1.29 | 1.31 | 1.35 | 1.40 | 1.50 | 1.46 | 1.50 | 1.52 | 1.53 |
| | | 2 | 1.11 | 1.14 | 1.20 | 1.24 | 1.41 | 1.33 | 1.38 | 1.40 | 1.41 |

[†]Warming ranges: 1=high warming condition across wine regions projected by CSIRO Mk3.5 model, 2=low warming condition across the wine regions projected by MEDRES Miroc3.2 model

#### 5.3.3.2 Titratable acidity under climate change

The biggest changes in median Cabernet Sauvignon TA under low warming range were about 3% increase for the Peel region by 2070, and 2% decrease in the Great Southern by 2050, essentially indicating no substantial changes. On the other hand, under high warming scenario, all regions are projected to have reduced median TA, which deepens over time (Table 5.4). Spatially, northeast parts of the Swan, Perth Hills, and inland parts of the Peel regions, and southeast of the Great Southern region are projected to experience the largest median TA decline for Cabernet Sauvignon (Figure 5.8). The median TA decline is more for these regions compared to the remainder of the regions, reaching the highest reduction of 12% for the Swan District followed by 6% decline for the Great Southern region by 2070 under high warming range compared to current level (Table 5.4).

Modelled Shiraz TA decreases are similar for most of the regions reaching the maximum decline of 15% for the Peel and the Great Southern regions by 2070 under high warming range. Interestingly, decreases in median TA projections are consistently lower for the central regions, especially for the Margaret River region with minimum declines of 3% and 7% by 2050 respectively under low and high warming ranges (Table 5.4; Figure 5.9). Spatially, inland parts of the Peel region are likely to experience the lowest

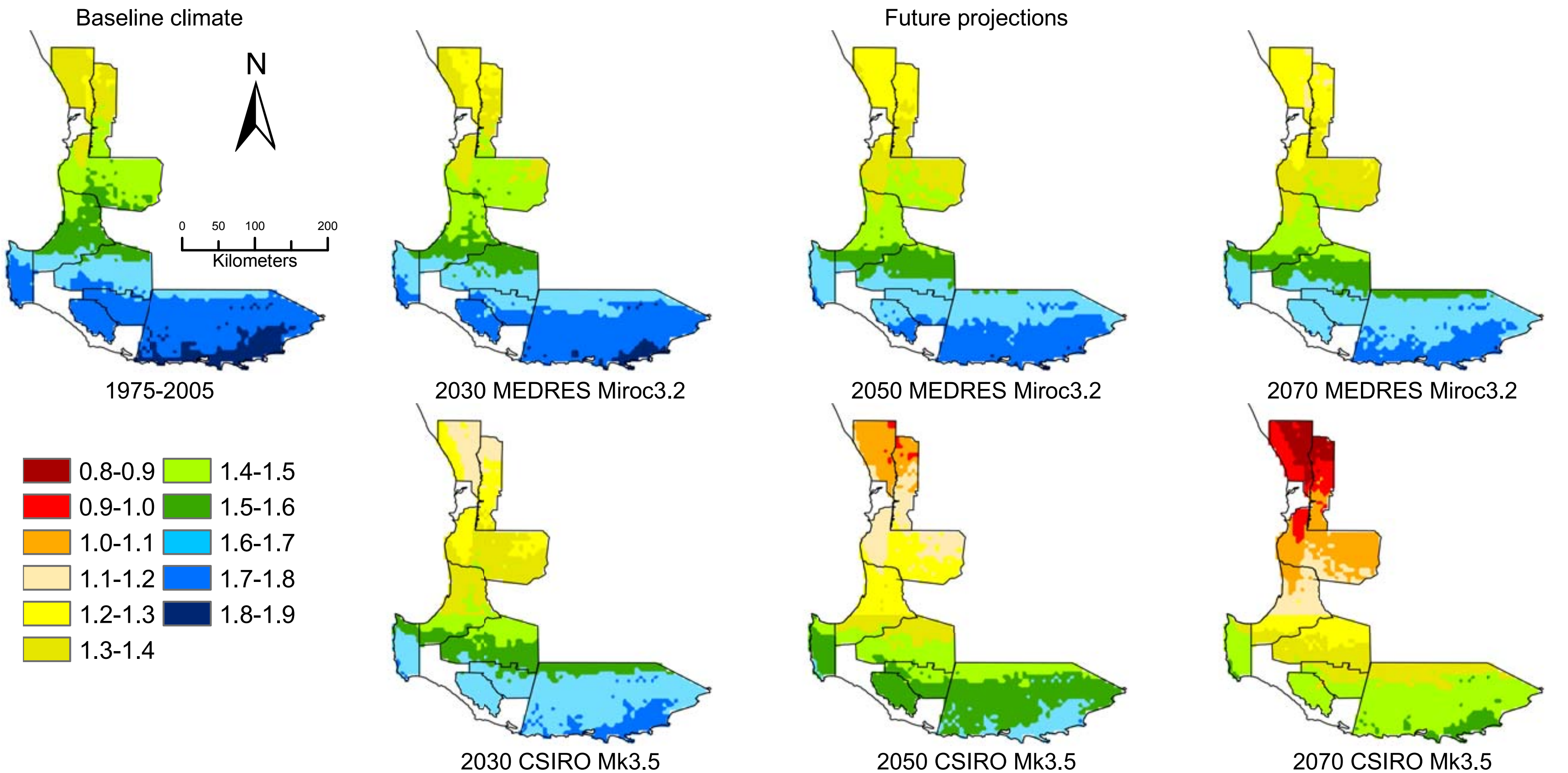


Figure 5.6 Current and projected Cabernet Sauvignon anthocyanin concentration at common maturity (total soluble solid of 22 °Brix) driven by mean January temperature (mg/g) under SRES A2 emission scenario

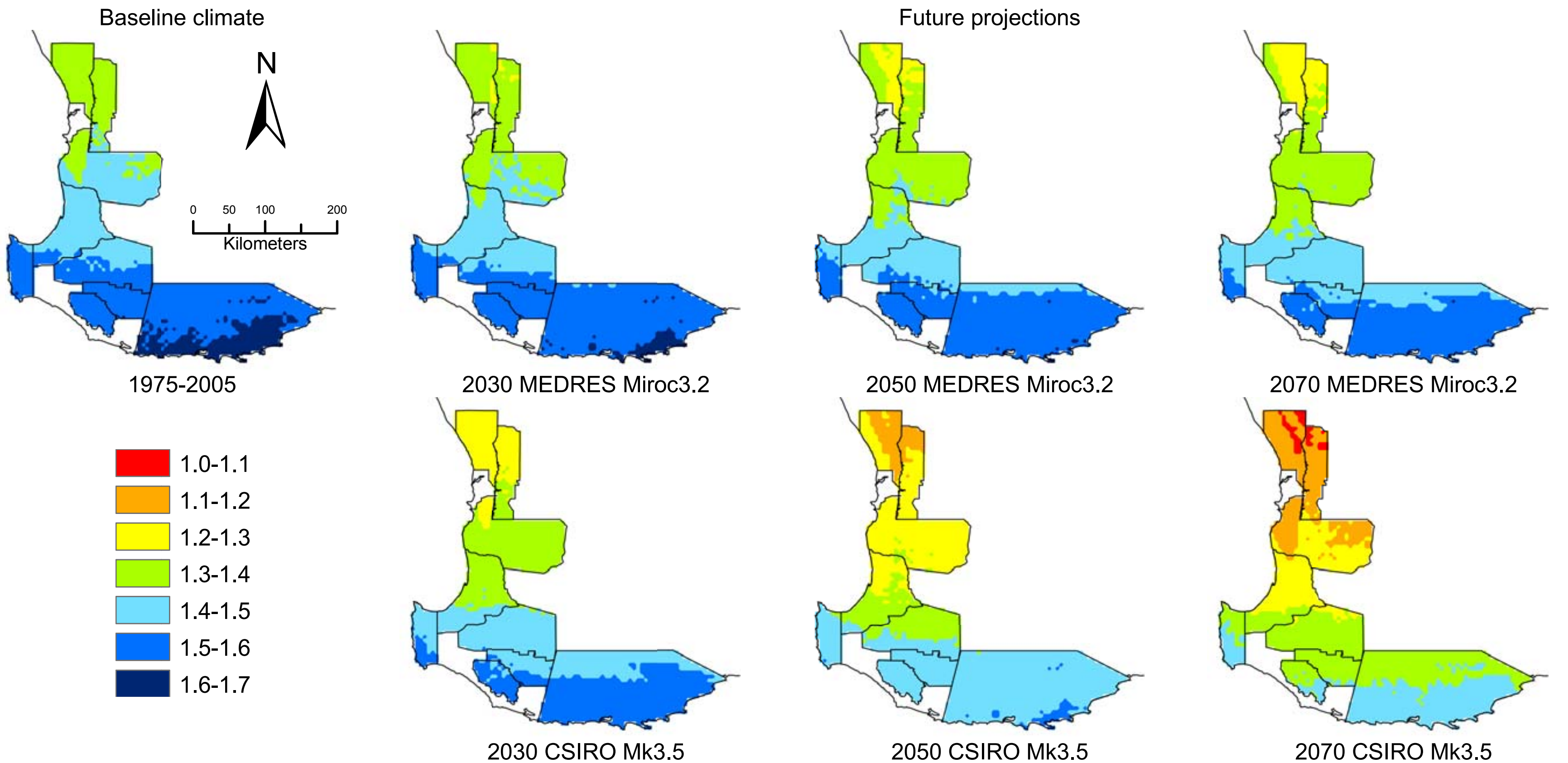


Figure 5.7 Current and projected Shiraz anthocyanin concentration at common maturity (total soluble solid of 22 °Brix) driven by mean January temperature (mg/g) under SRES A2 emission scenario

levels of Shiraz TA, declining from the current 5.5 to 6.0 (g/L) range to 5.0 to 5.5 (g/L) range by 2050 under high warming scenario (Figure 5.9).

Table 5.4 Current and projected median TA (g/L) at common maturity (total soluble solid of 22 °Brix) across WA wine regions under SRES A2 emission scenario

| Variety | Time and warming ranges[†] | | Swan District | Perth Hills | Peel | Geographe | Margaret River | Blackwood | Manjimup | Pemberton | Great Southern |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Cabernet | Current | | 6.81 | 6.48 | 6.35 | 6.75 | 8.09 | 6.62 | 7.29 | 7.79 | 7.86 |
| Sauvignon | 2030 | 1 | 6.88 | 6.62 | 6.45 | 6.83 | 8.14 | 6.72 | 7.32 | 7.87 | 7.86 |
| | | 2 | 6.53 | 6.37 | 6.33 | 6.73 | 7.97 | 6.58 | 7.09 | 7.54 | 7.52 |
| | 2050 | 1 | 6.76 | 6.55 | 6.49 | 6.86 | 8.06 | 6.69 | 7.25 | 7.73 | 7.69 |
| | | 2 | 6.18 | 6.06 | 6.20 | 6.60 | 7.92 | 6.57 | 7.07 | 7.46 | 7.38 |
| | 2070 | 1 | 6.73 | 6.51 | 6.52 | 6.87 | 8.08 | 6.70 | 7.23 | 7.71 | 7.66 |
| | | 2 | 5.98 | 5.90 | 6.06 | 6.51 | 7.89 | 6.61 | 7.10 | 7.49 | 7.42 |
| Shiraz | Current | | 7.25 | 6.85 | 6.92 | 7.56 | 9.77 | 7.27 | 8.52 | 9.73 | 9.45 |
| | 2030 | 1 | 7.27 | 6.89 | 6.91 | 7.53 | 9.78 | 7.24 | 8.45 | 9.62 | 9.32 |
| | | 2 | 6.89 | 6.49 | 6.47 | 7.14 | 9.48 | 6.88 | 8.03 | 9.12 | 8.79 |
| | 2050 | 1 | 7.12 | 6.72 | 6.72 | 7.38 | 9.57 | 7.09 | 8.28 | 9.38 | 9.09 |
| | | 2 | 6.35 | 5.92 | 5.88 | 6.58 | 9.07 | 6.37 | 7.48 | 8.51 | 8.17 |
| | 2070 | 1 | 7.03 | 6.62 | 6.60 | 7.28 | 9.45 | 6.99 | 8.16 | 9.22 | 8.93 |
| | | 2 | 6.44 | 5.95 | 5.89 | 6.57 | 9.10 | 6.35 | 7.41 | 8.38 | 7.99 |
| Chardonnay | Current | | 9.08 | 8.51 | 8.43 | 8.36 | 10.17 | 8.22 | 9.35 | 9.97 | 11.27 |
| | 2030 | 1 | 9.15 | 8.77 | 8.45 | 8.37 | 10.29 | 8.21 | 9.29 | 9.87 | 11.13 |
| | | 2 | 7.96 | 7.66 | 7.34 | 7.40 | 9.67 | 7.50 | 8.17 | 8.65 | 9.74 |
| | 2050 | 1 | 8.79 | 8.44 | 8.13 | 8.14 | 10.29 | 8.22 | 8.99 | 9.54 | 10.68 |
| | | 2 | 6.83 | 6.58 | 6.39 | 6.47 | 9.06 | 6.54 | 7.47 | 8.01 | 9.14 |
| | 2070 | 1 | 8.72 | 8.36 | 8.01 | 8.11 | 10.33 | 8.25 | 9.02 | 9.51 | 10.62 |
| | | 2 | 5.23 | 5.08 | 5.06 | 5.33 | 8.45 | 5.80 | 6.64 | 7.19 | 8.32 |

[†]Warming ranges: 1=high warming condition across wine regions projected by CSIRO Mk3.5 model, 2=low warming condition across the wine regions projected by MEDRES Miroc3.2 model

The Chardonnay TA model projects a decline in median Chardonnay TA for all regions progressing with time with the exception of a few regions that showed a slight increase by 2030 under low warming scenario. The largest declines in median TA levels were between 40% and 42% for Swan District, Perth Hills, Peel and the northeast Geographe regions by 2070, under high warming scenario (Table 5.4; Figure 5.10). Under the same warming scenario, decreases in median TA levels are projected about 30% in the southern wine regions. Levels of Chardonnay TA at maturity are projected to be less impacted by climate change in the Margaret River region compared to the other wine regions. The biggest changes for this region were 17% and 2% of current level TA by 2070, respectively, under the high and low warming scenarios (Table 5.4; Figure 5.10).

#### 5.3.3.3 Grape pH levels under projected climate change

As expected, the current distribution of modelled Cabernet Sauvignon pH levels is lower in cooler and higher in warmer areas. However, the projected ranges are narrow: between 3.25 to 3.45 units for Cabernet Sauvignon and Shiraz, 3.10 to 3.25 units for Chardonnay at a TSS of 22 °Brix (Figures 5.11 to 5.13). The current levels of pH are projected to increase over time under climate change, but the magnitudes, and the rates of changes were varied between the climate warmings.

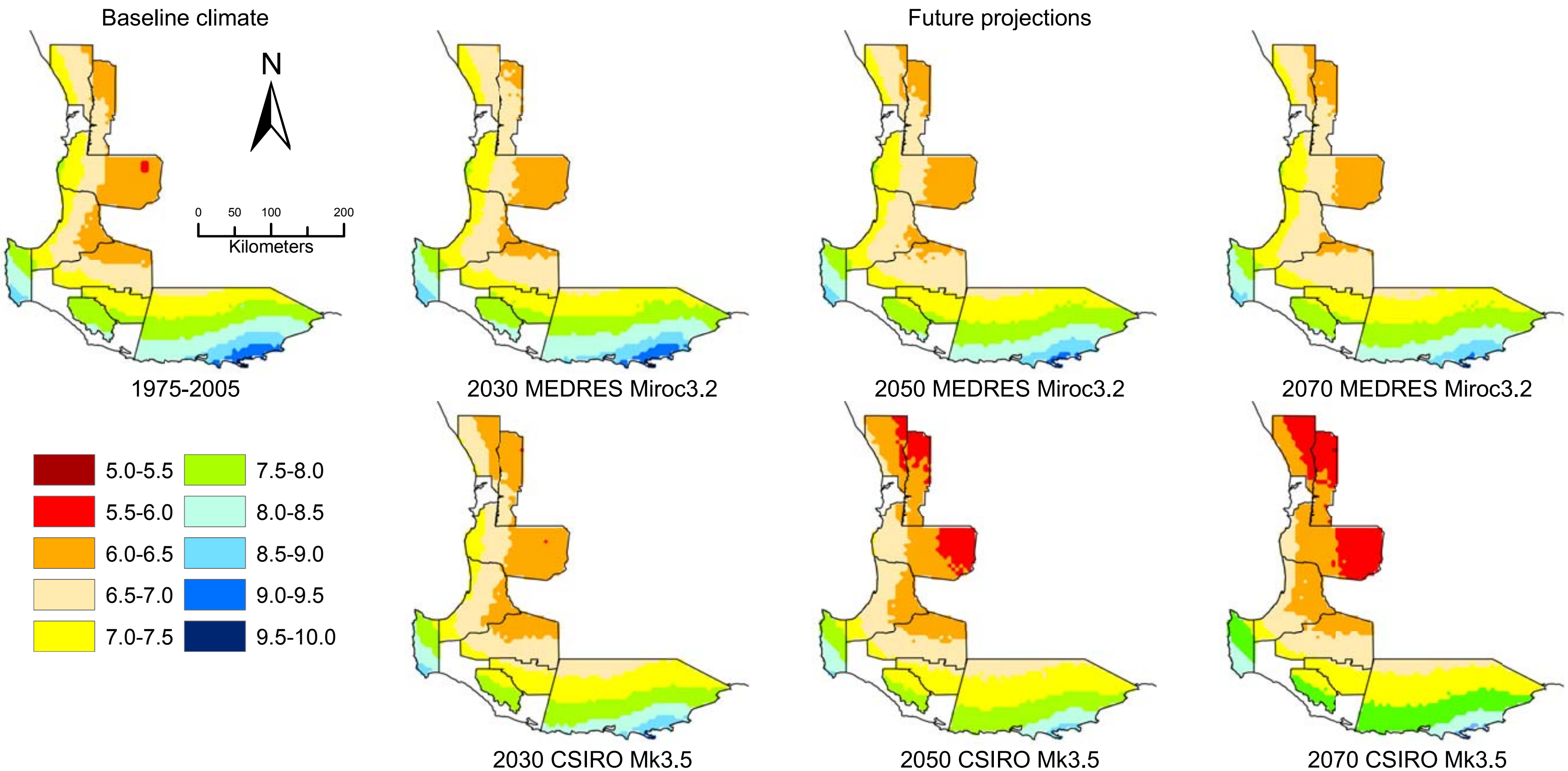


Figure 5.8 Current and projected Cabernet Sauvignon titratable acidity at common maturity (total soluble solid of 22 °Brix) driven by growing season diurnal range and ripening period minimum temperature (g/L) under SRES A2 emission scenario

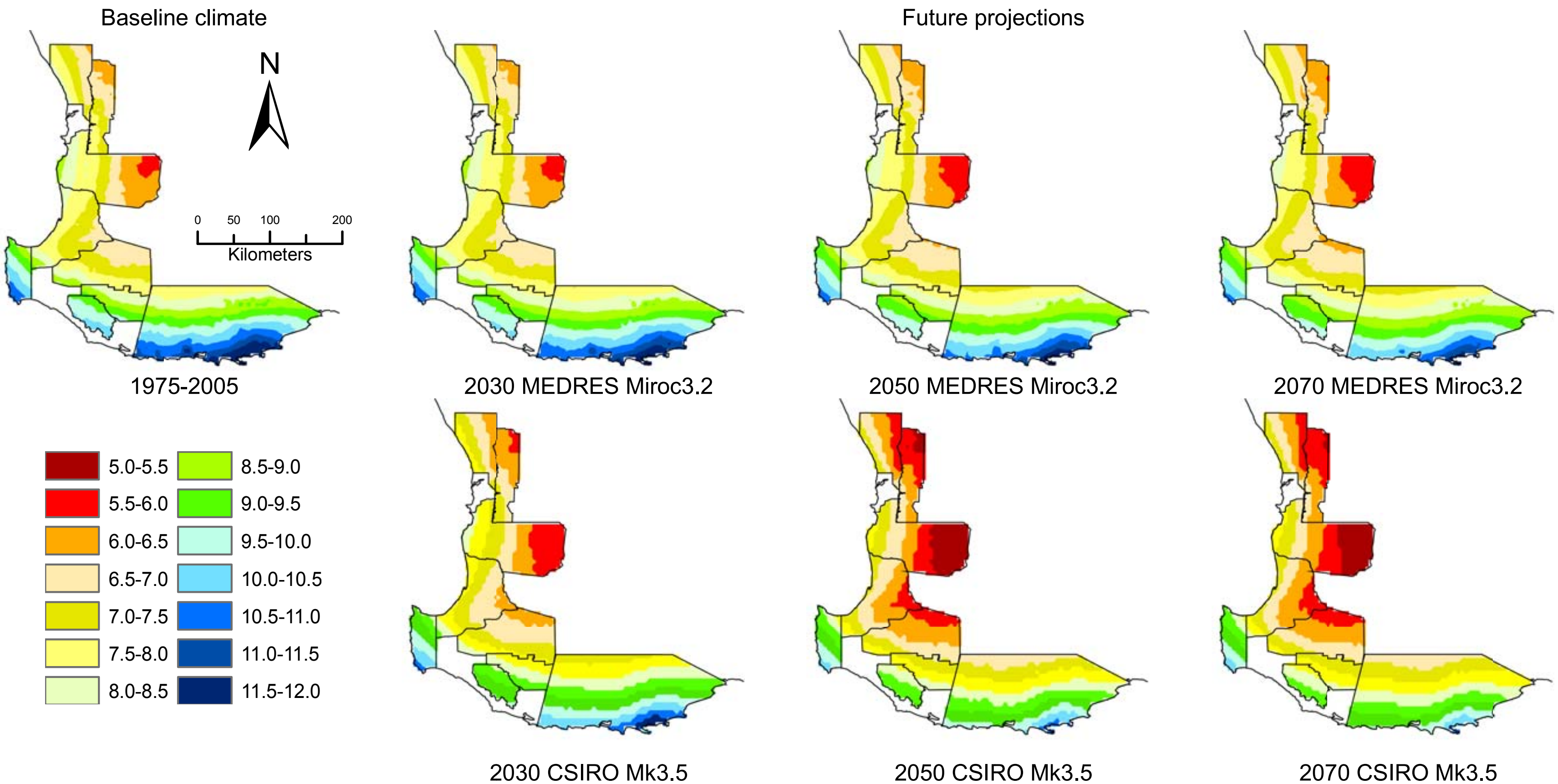


Figure 5.9 Current and projected Shiraz titratable acidity at common maturity (total soluble solid of 22 °Brix) driven by October to February diurnal range and growing season total rainfall (g/L) under SRES A2 emission scenario

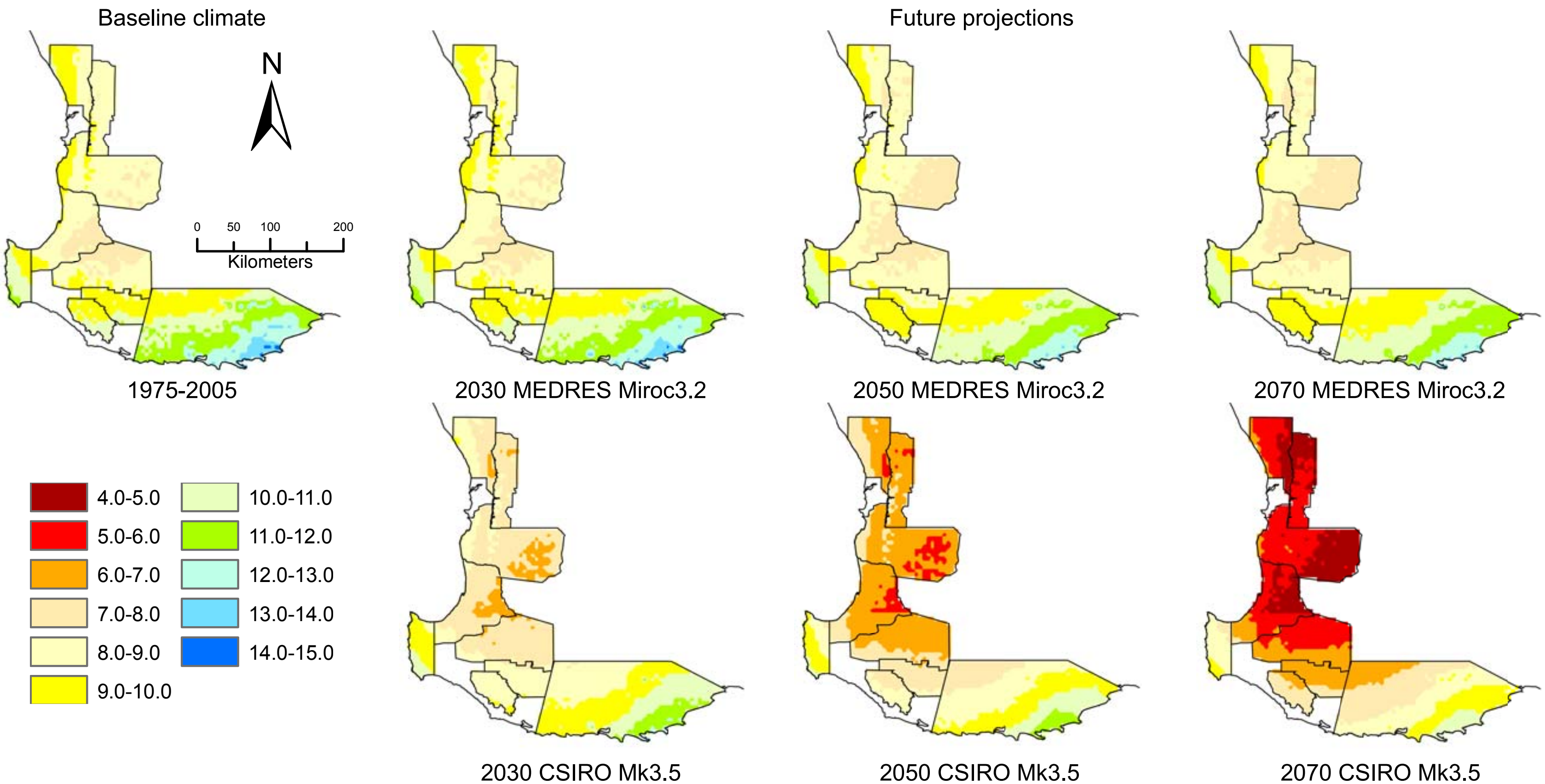


Figure 5.10 Current and projected Chardonnay titratable acidity at common maturity (total soluble solid of 22 °Brix) driven by February diurnal range, ripening period minimum temperature, and average radiation in October (g/L) under SRES A2 emission scenario

Under low warming scenario, the current distribution of pH is projected to shift southward across the varieties of this study, however the magnitudes were generally small with a maximum of 0.05 units by 2070 regardless of the regions (Figures 5.11 to 5.13). On the other hand, more intense increases in current pH levels are projected with high warming range. For example, the pH increase under high warming scenario by 2030 is similar to what is projected under low warming by 2070 for all three varieties.

The pH increases were not uniform under high warming scenario. Contrary to expectation, the Chardonnay pH levels are projected to be gradually decreasing in some areas of Margaret River, and the southern regions by 2030 and 2050 and, then increase across the regions by 2070. By 2070, the southern parts of the Great Southern and Margaret River regions are projected to have pH levels 0.15 units higher for Cabernet Sauvignon and Shiraz at the common maturity compared pH levels under the current climate. Meantime, the changes in pH in warmer regions, (Swan District and Perth Hills) are likely to increase by 0.3 units reaching 3.65 to 3.75 for Cabernet Sauvignon and Shiraz, and by 0.25 units for Chardonnay reaching 3.52 units (Figure 5.11; Table 5.5).

Table 5.5 Current and projected median pH at common maturity (total soluble solid of 22 °Brix) across WA wine regions under SRES A2 emission scenario

| Variety | Time and warming ranges [†] | | Wine regions: Swan District | Perth Hills | Peel | Geographe | Margaret River | Blackwood | Manjimup | Pemberton | Great Southern |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Cabernet Sauvignon | Current | | 3.41 | 3.39 | 3.35 | 3.32 | 3.26 | 3.29 | 3.27 | 3.26 | 3.25 |
| | 2030 | 1 | 3.43 | 3.39 | 3.36 | 3.32 | 3.28 | 3.30 | 3.27 | 3.26 | 3.27 |
| | | 2 | 3.48 | 3.45 | 3.40 | 3.36 | 3.29 | 3.33 | 3.31 | 3.30 | 3.30 |
| | 2050 | 1 | 3.45 | 3.41 | 3.38 | 3.33 | 3.29 | 3.31 | 3.28 | 3.27 | 3.27 |
| | | 2 | 3.53 | 3.49 | 3.44 | 3.38 | 3.29 | 3.34 | 3.31 | 3.30 | 3.30 |
| | 2070 | 1 | 3.47 | 3.43 | 3.40 | 3.34 | 3.29 | 3.31 | 3.29 | 3.28 | 3.28 |
| | | 2 | 3.70 | 3.64 | 3.59 | 3.53 | 3.39 | 3.46 | 3.42 | 3.41 | 3.41 |
| Shiraz | Current | | 3.38 | 3.36 | 3.33 | 3.30 | 3.26 | 3.28 | 3.26 | 3.26 | 3.25 |
| | 2030 | 1 | 3.40 | 3.37 | 3.34 | 3.31 | 3.26 | 3.29 | 3.26 | 3.25 | 3.26 |
| | | 2 | 3.46 | 3.42 | 3.38 | 3.34 | 3.28 | 3.31 | 3.29 | 3.29 | 3.29 |
| | 2050 | 1 | 3.43 | 3.39 | 3.35 | 3.31 | 3.27 | 3.30 | 3.27 | 3.26 | 3.26 |
| | | 2 | 3.51 | 3.46 | 3.41 | 3.36 | 3.27 | 3.32 | 3.29 | 3.28 | 3.28 |
| | 2070 | 1 | 3.45 | 3.40 | 3.37 | 3.32 | 3.27 | 3.30 | 3.28 | 3.27 | 3.27 |
| | | 2 | 3.67 | 3.62 | 3.56 | 3.51 | 3.37 | 3.43 | 3.40 | 3.39 | 3.39 |
| Chardonnay | Current | | 3.23 | 3.21 | 3.20 | 3.19 | 3.16 | 3.20 | 3.18 | 3.18 | 3.18 |
| | 2030 | 1 | 3.23 | 3.21 | 3.20 | 3.18 | 3.16 | 3.19 | 3.18 | 3.17 | 3.18 |
| | | 2 | 3.27 | 3.24 | 3.22 | 3.20 | 3.16 | 3.19 | 3.18 | 3.18 | 3.18 |
| | 2050 | 1 | 3.25 | 3.22 | 3.21 | 3.19 | 3.16 | 3.19 | 3.18 | 3.17 | 3.18 |
| | | 2 | 3.30 | 3.27 | 3.23 | 3.20 | 3.15 | 3.18 | 3.17 | 3.16 | 3.17 |
| | 2070 | 1 | 3.26 | 3.23 | 3.22 | 3.19 | 3.16 | 3.19 | 3.18 | 3.17 | 3.18 |
| | | 2 | 3.46 | 3.40 | 3.36 | 3.31 | 3.22 | 3.27 | 3.25 | 3.24 | 3.25 |

[†]Warming ranges: 1=high warming condition across wine regions projected by CSIRO Mk3.5 model, 2=low warming condition across the wine regions projected by MEDRES Miroc3.2 model

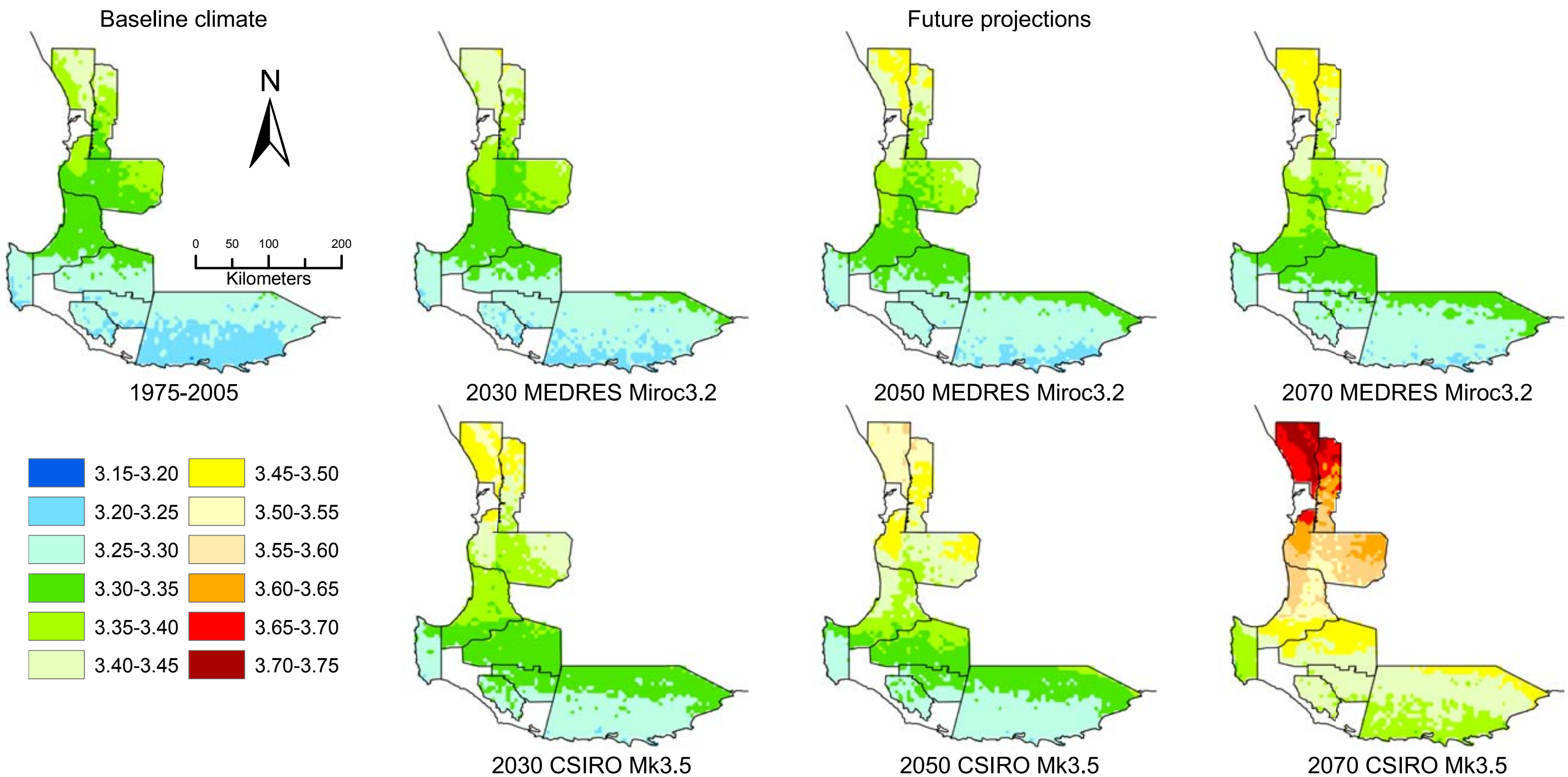


Figure 5.11 Current and projected Cabernet Sauvignon pH levels at common maturity (total soluble solid of 22 °Brix) driven by growing season growing degree day, and vapour pressure deficit in October under SRES A2 emission scenario

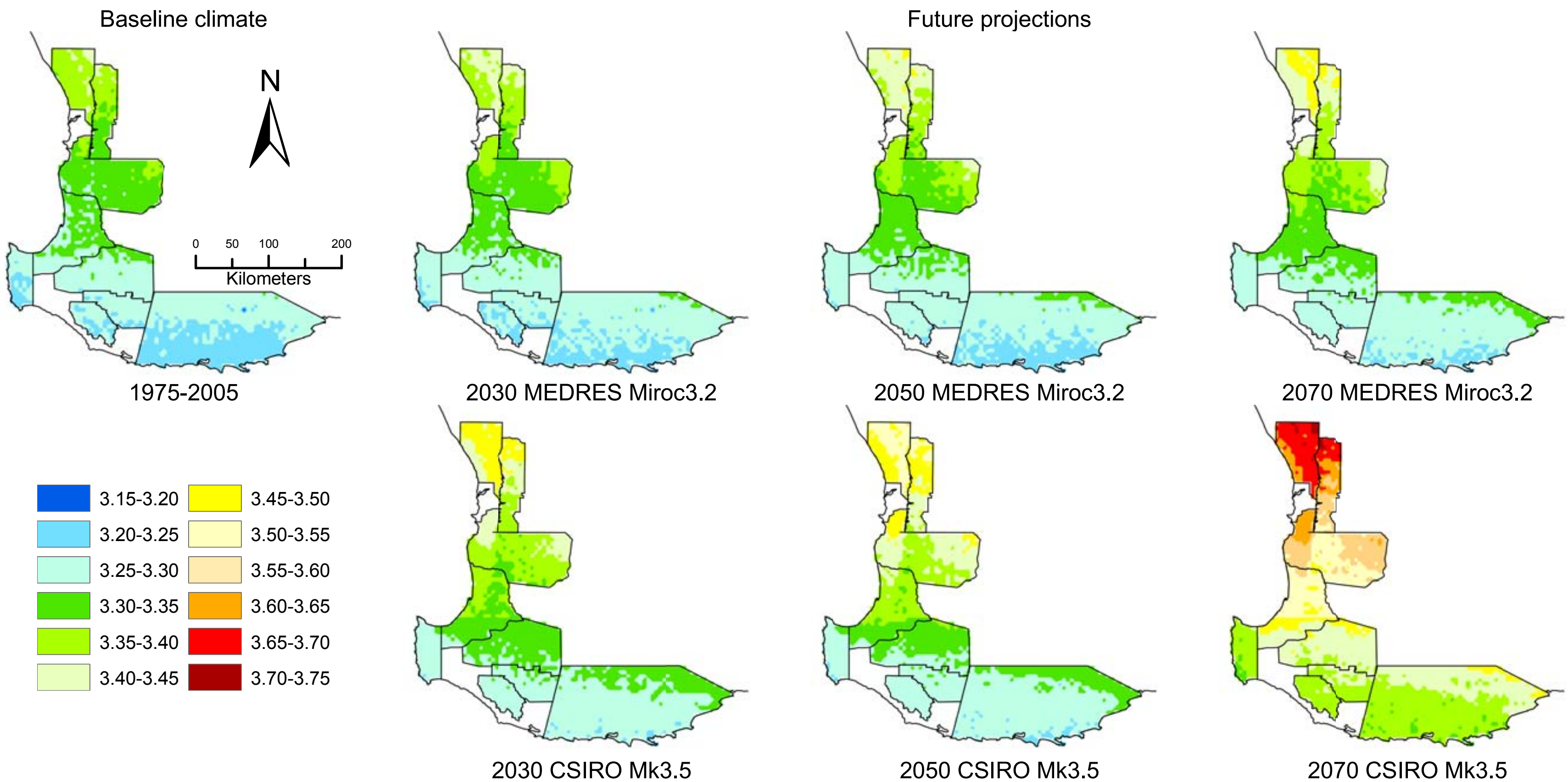


Figure 5.12 Current and projected Shiraz pH levels at common maturity (total soluble solid of 22 °Brix) driven by growing season growing degree day, and vapour pressure deficit in October under SRES A2 emission scenario

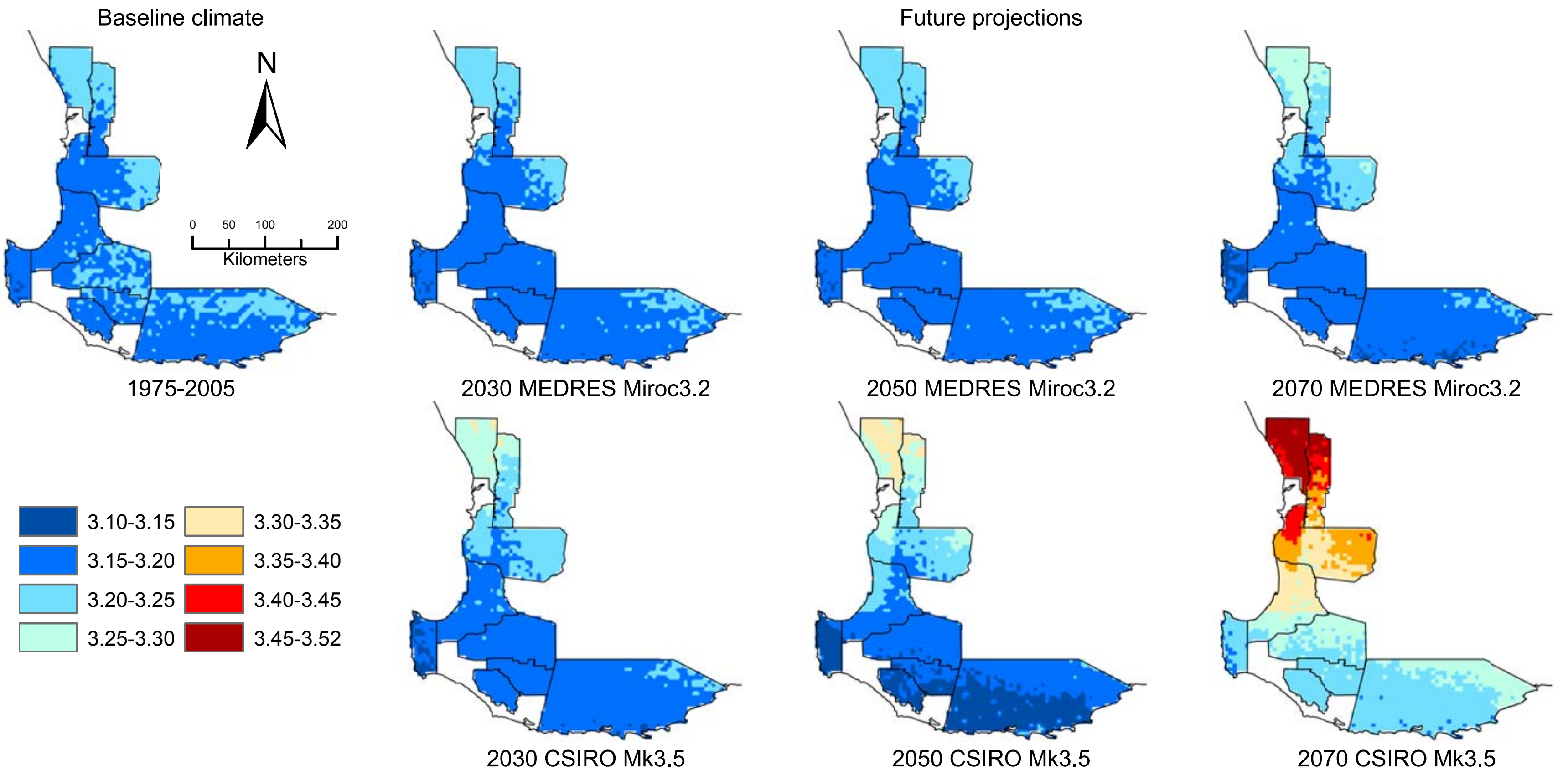


Figure 5.13 Current and projected Chardonnay pH levels at common maturity (total soluble solid of 22 °Brix) driven by growing season growing degree day, and vapour pressure deficit in October

## 5.4 Discussion

### 5.4.1 Projections of maturity dates

The modelled maturity dates from this study show that the current and future variation among the regions are greater than the temporal (under climate change) changes (Figure 5.5). This is a reflection of the wider ranges in the average October to February temperatures among the regions than between the current period and high warming scenario for 2070.

Changes in the grape maturity dates under climate change will be spatially asymmetric across the study regions: smaller shifts in maturity are projected in current warm areas (northern regions) than the current cooler regions in the south. Based on the grape maturity models presented here Cabernet Sauvignon, Shiraz, and Chardonnay maturity dates are projected to be 11 days earlier in the warmer Swan District and 30 to 36 days earlier in the Great Southern region when assessed at a constant 2°C degree warming. These findings are in agreement with other reports. For example, according to Dry (1988), a 2°C warmer temperature results in 12 to 30 days earlier harvest depending on variety. The asymmetric variations in grape maturity dates projected by the regression models seem to be supported by the BEDD concept (Gladstones, 1992), which postulates that high average temperature (over 19°C) is ineffective for vine physiology. However, the BEDD approach lacked resolution to adequately predict grape maturity across different regions compared to the regression models. For example, when assessed by the BEDD approach Margaret River and inland parts of the Peel and Geographe regions had the same maturity date groups under current climate, while the regression model produced four different maturity date groups (Figures 5.2 to 5.5).

Under high warming climate scenario, the projected median maturity dates for Cabernet Sauvignon were generally earlier than the maturity dates that were derived from the BEDD accumulation approach (Hall and Jones, 2009). This disparity is not surprising since the current study modelled the maturity dates at a constant TSS of 22 °Brix, while the BEDD based maturity concept was based on practical observations for climate conditions for making dry or semi-sweet wines without measurable characteristics for the maturity (Gladstones, 1992). In practice, grapes tend to be left on vines beyond a TSS of at 22 °Brix in order to attain fully developed flavour profiles unless required for making special wine styles such as sparkling wine.

On the other hand, there were only 2 day differences between projected Cabernet Sauvignon maturity dates from this study, under low warming condition, and the projected harvest dates reported by Webb et al. (2007) who utilized the VineLOGIC vineyard simulation model at the same TSS for Margaret River by the years 2030 and 2050. The projected Chardonnay maturity dates from this study and Webb et al. (2007) differed by up to 7 days by 2030 and 2050. Chardonnay maturities have been consistently projected earlier than Cabernet Sauvignon and Shiraz at the same designated maturity, and this is in line with the different heat requirements that each genotypes requires to reach maturity (Gladstones, 1992) (Figure 5.4). Moreover, the projected grape maturities under climate change are in agreement with the trends in shortening winegrape phenology, and advanced maturity that have been attributed to climate warming to date (Jones and Davis, 2000a, Petrie and Sadras, 2008).

### 5.4.2 Projected grape quality attributes under climate change

Sugar, acidity, and colour are important attributes of grape berry quality. When sugar accumulation, which is considered the main indicator of grape maturity, reaches an acceptable range for optimum alcohol level for wine, other quality attributes such as acid or colour, become additional quality indicators to consider for overall fruit quality (Francis et al., 2005). The general post-véraison interrelationships between the quality attributes (for example the acidity decrease while pH increases or anthocyanin concentration increase) with time are well known (Coombe and Iland, 1987, Coombe, 1992, Robinson and Davies, 2000, Conde et al., 2007). However, relative rates of change, and thus the final levels of the quality attributes at harvest, are heavily dependent upon weather conditions when other non-climatic factors are constant (Jackson and Lombard, 1993). To our knowledge, there are no standard definitions of grape and wine quality, despite some attempts to characterize wine quality based on sugar to acid ratio or sugar and pH multiplications (Ough and Alley, 1970, Sinton et al., 1978, Coombe et al., 1980). In addition, the grape quality attributes for this study were investigated at a constant TSS to examine the climate impacts on the quality attributes. Therefore, in the sections below potential impacts of climate change on wine quality are discussed qualitatively.

### 5.4.3 Trends in anthocyanin concentrations and implications for wine quality

Anthocyanin concentrations in wine determine the wine colour, which is one of the important characteristics that contribute to overall red wine quality. Somers and Evans (1974) demonstrated significant positive correlation between wine quality ratings given by independent judges and colour density of Cabernet Sauvignon and Shiraz wines.

Under the current climate regime, projected Cabernet Sauvignon and Shiraz anthocyanin concentrations in WA wine regions range from 1.35 (mg/g) in the warmer Swan District to up to 1.9 (mg/g) in the Great Southern region (Figures 5.6 and 5.7). Shiraz and Cabernet Sauvignon typically produce medium to intense coloured wines, and anthocyanin concentrations above 1.7 (mg/g per fresh berry weight) are required to produce intensely red coloured wine (Iland et al., 2004). Gradual decreases in Cabernet Sauvignon and Shiraz anthocyanin concentrations under the projected climate change suggest reduction in wine quality in most of the wine growing regions of WA. Under high warming scenario, by 2050, all WA wine regions are modelled to produce Cabernet Sauvignon grapes with less than the 1.7 (mg/g) anthocyanin concentrations indicating an overall wine quality decrease in the WA wine growing regions.

Patterns of changes in Cabernet Sauvignon and Shiraz anthocyanin concentrations under high and low warming scenario are similar: all showing a southward shifting of current spatial distributions. This is suggestive of justification for relocation of vineyards to the south to maintain the current grape quality under climate change and has been proposed by other researchers (Tate, 2001, Webb et al., 2008a). However, spatial distributions of predicted anthocyanin concentrations suggest that the success of vineyard shifting is likely be limited and dependent on the magnitude of the future warming. For example, under the most optimistic (low warming) scenario, current areas that have the potential to produce Cabernet Sauvignon grape with anthocyanins levels more than 1.7 (mg/g fresh weight) will unlikely be available for the northern half and northeastern parts of central Margaret River, northern areas of Manjimup and the Great Southern region by 2030. Collectively these area represent the larger proportion of the WA wine industry.

Cabernet Sauvignon anthocyanin concentrations of above 1.7 (mg/g per fresh berry weight) is projected only in the Great Southern region (mostly in southern parts) by 2070 (Figure 5.6). Declines in the anthocyanin concentrations are projected to be more intense under high warming scenario. By 2070, Cabernet Sauvignon and Shiraz grapes in areas from the southern part of Geographe to the Great Southern are projected to have the same levels of anthocyanin concentrations, currently found in areas from the Swan District to northern Geographe (Figure 5.6 and 5.7). Adaptation by shifting the vineyards may be possible for vineyards in current northern regions, but for the southern regions opportunities will likely be limited by capital costs, availability of land and any future declines in rainfall. Thus, with limited opportunity for adaptation future climate change is likely to cause deteriorated grape and wine quality in currently established WA wine regions or diminished regional characteristics in coming decades.

### 5.4.4 Trends of acidity change and its implication for wine quality

According to modelling results, changes in the TA level under climate change varied across regions and varieties; in the majority of cases our models show decreasing TA, while some models indicate slight increases in TA depending on the climate warming magnitude (Table 5.4). The greatest projected decreases in median TA, compared with current levels, is projected to be 12% for Cabernet Sauvignon in Swan District, 15% for Shiraz in Peel and

Great Southern regions, and 42 % for Chardonnay in Swan District in the coming decades (Table 5.4; Figures 5.8 to 5.10).

It is long accepted that balanced acid properties help wine to maintain freshness, in addition to determining the taste of wines (Mato et al., 2005, Conde et al., 2007, Sweetman et al., 2009). However, there is no commonly accepted TA range for producing quality wines. Winkler (1974) suggested a TA range between 3 to 9 (g/L) to be optimum for wine making. Conde et al. (2007) advised a narrower range of 6.5 to 8.5 (g/L). Jackson and Lombard (1993) stated that wine TA levels above 10 (g/L) or below 6 to 7 (g/L) TA levels are too tart or bland, respectively. According to modelling results of this study, the majority of the WA grape growing regions have TA levels close to the optimum for making balanced wine. However, under climate change, the median TA levels across the wine regions are projected to be lower than the suggested TA levels by Conde et al. (2007) and Jackson and Lombard (1993). Potential consequences of the decreased grape acidity for the above regions are likely to result in inferior quality wines requiring wineries to add additional acids to balance the low levels of organic acids in musts and increase the wine's stability. Acid addition involves extra cost for the wineries and the resulting wine is considered less satisfactory compared with naturally balanced acids (Gladstones, 1992).

The reductions in Chardonnay pH levels by 2030 and 2050 for the Margaret River, Blackwood, and the southern regions, and increases by 2070 under high warming scenario are inconsistent and counterintuitive. This inconsistency might be due to a deficiency in the climate driven models to predict the pH levels, which are also strongly regulated by other factors such as grape organic acids (Boulton, 1980). Soil moisture availability also could play a role for grape pH through limiting the water uptake by vines, thus impacting the potassium content, which is likely to impact the grape pH levels (Rankine et al., 1971, Boulton, 1980, Gladstones, 1992). Perhaps, study of the pH modelling as a function of climate variables deserves further investigation.

Nevertheless, despite the above shortcomings, grape pH levels were projected to be increasing across varieties and regions overall. However, the impacts of the grape pH increases as modelled at 22 °Brix TSS maturity may not be that alarming. With the modelling results of this study, the highest values of current pH at 22 °Brix maturity were 3.40-3.45 for Cabernet Sauvignon and Shiraz, and 3.20-3.25 for Chardonnay and these values were indicated in the Swan District region by 2070 at the common fruit maturity level. According to Jackson and Lombard (1993) pH levels above 3.60 might cause problems by permitting increased activity of micro-organisms, lowering the anthocyanins levels, and reducing free $SO_2$ content and reducing the ability of wines to age. Similarly La Rosa (1955) claimed that the best quality table wines were produced by grapes with pH less than 3.40 while good dessert wines could be produced from grapes with pH between 3.50-3.60.

## 5.5 Conclusion

In this study we aimed to evaluate potential impacts of climate change on winegrape fruit quality across the WA wine regions. Results of our study indicate that some of the key grape quality attributes (anthocyanins and acidity) will likely decline to an extent that fruit might become less suitable for making naturally balanced premium wine. Declines in wine quality likely to occur unless effective adaptive measures are undertaken. The extent of the impacts on grape quality are also likely to be region specific, and the northern regions, particularly the Swan District and Perth Hills regions, are projected to be under greater pressure than the southern cooler regions. Overall, the current distribution of grape quality attributes is projected to shift southward in the future and may well alter the current market positioning of the wine industry within the WA.

# CHAPTER 6. CHANGES IN PREMIUM WINE PRODUCTION CONDITIONS FOR WESTERN AUSTRALIAN WINE REGIONS

## 6.1 Introduction

The climate conditions of the Western Australian (WA) wine regions are projected to change in the future and the impacts on viticulture are likely to be negative (Webb, 2006; Hall and Jones, 2009; Chapters 4 and 5). For example, under A2 emission scenario, average growing season temperature (GST) is projected to be as much as 3 to 4.5°C warmer across WA wine regions by 2070 compared with the current climate (see Chapter 4). The frequency of extreme hot days, and the average temperature during grape maturation are likely to increase, whilst rainfall is projected to decrease (see Chapter 4). Key quality attributes of Cabernet Sauvignon, Shiraz and Chardonnay are likely to decline (see Chapter 5). Collectively, the above findings indicate that the WA wine industry might be confronting new climate conditions that are likely to require the industry to take adaptive measures for its continued success.

Recommended adaptation strategies for the Australian wine industry in response to increasing temperature include:

1. Changes in current winegrape varieties or shifting of wine growing regions
2. Changes in management practices, such as the use of dormancy breakers for better bud break; introduction of genetically modified vines or yeast, and
3. Changes in winemaking technology and winery infrastructure to accommodate the climate impacts (Anderson et al., 2008, Webb and Barlow, 2008).

Implementation of any of these adaptations might incur costs and careful detailed spatial and temporal climate analyses are needed before initiating such action.

This study investigated spatial and temporal changes in the average GST with the aim of providing background climate information for adapting WA premium wine production to projected changes in climate. This study takes into consideration the potential impacts of other climate conditions such as winter chilling, disease pressure, and vapour pressure deficit (referred to hereafter as stress variables) that limit winegrape growth. The present study extends the climate change impact study by Hall and Jones (2009) by including more climate model projections; and studies by Hall and Jones (2010), and Jones et al., (2010) by utilizing future climate analyses. The selection of average GST for this study as the main climate criterion for premium wine production was based on its correlations with other climate indices that describe viticultural climate conditions. For example, the average GST is highly correlated with GDD, Huglin's index and biologically effective degree days, that describe grape growing conditions in Australia (Hall and Jones, 2010). Moreover, it has also been reported that average GST accounts up to 60% of variations in vintage ratings (Jones et al., 2005).

## 6.2 Materials and methods

### 6.2.1 Climate data

Consistent with previous chapters of this thesis, downscaled outputs of CSIRO Mk3.5 and MEDRES Miroc3.2 climate models were used as representations of high and low warming climate change ranges across the WA wine regions. Study areas, methods for climate model selection, downscaling and GST calculations were described in Chapter 4.

#### 6.2.1.1 Growing season temperature categories

Jones (2007) classified the winegrape GST into 4 classes: cool 13-15°C, intermediate 15-17°C, warm 17-19°C, and hot 19-24°C. According to this classification different winegrape varieties have different but overlapping GST ranges for producing premium quality wine (Jones, 2007). For example, the cool to intermediate GST range of 14-17°C is suitable for Chardonnay, while the intermediate to warm range GST of 16-19°C is suited to premium quality Shiraz. Hall and Jones (2009) used the above classification, with the slight modification of splitting the hot category into hot 19-21°C, and very hot 21-24°C for Australian grape growing conditions. In Chapter 5 of this thesis it was indicated that classification of GST with 1.5°C intervals were too coarse to capture spatial differences between intra regional or in some cases interregional GST variations. Therefore, for this study, the GST categories of Hall and Jones (2009) were split into Lower (L) and Higher (H) sub-categories for detailed spatial analysis across the study regions (Table 6.1). An average GST range of more than 24°C is denoted as unsuitable for premium wine production.

Table 6.1 Average Growing Season Temperature category

| GST categories and relevant range by Hall and Jones (2009) | | GST categories and ranges used for this study | |
|---|---|---|---|
| Cool | (13-15°C) | N/A† | |
| Intermediate | (15-17°C) | N/A† | |
| | | Intermediate | (16-17°C) |
| Warm | (17-19°C) | Warm L | (17-18°C) |
| | | Warm H | (18-19°C) |
| Hot | (19-21°C) | Hot L | (19-20°C) |
| | | Hot H | (20-21°C) |
| Very Hot | (21-24°C) | Very hot L | (21-22.5°C) |
| | | Very hot H | (22.5-24°C) |
| | | Unsuitable | (> 24°C) |

L and H denotes lower and higher, respectively, †Results of Chapter 5 indicated that the minimum average GST for the study regions was 16.0°C, Cool and Intermediate L ranges are not used for this study

#### 6.2.1.2 Winter chilling

Different approaches have been used for studying chilling impacts during dormancy on winegrape budbreak. Some have used, under controlled conditions, minimum temperatures less than 2°C (Kliewer and Soleimani, 1972), or less than 6°C (Botelho et al., 2007) as the critical temperature below which chill units accumulate during dormancy. Others consider a period of at least 7 consecutive days with a mean daily temperature below 10°C (Lavee and May, 1997), or duration of minimum temperature below 5°C (Lyons and Considine, 2007) as thresholds of winegrape chilling. It is also reported that, in field conditions, the duration of exposure to the critical chilling temperature, and the magnitude of subsequent warming on the next day following the night, all impact the chill accumulation (Allan, 2003). Durations of exposure and actual temperature values below the chill accumulation threshold are required for some detailed chill accumulation models such as the Utah chill model (Lacey and Antoine, 2007). Nevertheless, there is no quantified exact minimum threshold of chilling requirement for winegrapes (Williams, 2000). In this study, a compromise metric - the number of days with a minimum temperature of less than 8°C during the June to August period - is used to assess whether winegrape chilling requirements across WA wine regions under future climate change.

#### 6.2.1.3 Winegrape disease pressure

Downy mildew, Powdery mildew, and Botrytis are the most common diseases for Australian viticulture (Emmett et al., 1992). Incidences of these fungal diseases can be promoted under warm and moist weather conditions (Magarey et al., 1994). Therefore, any increases in temperature and humidity will likely increase conditions for fungal disease outbreak. For this study, the Branas Index (BI) (Branas, 1974) was used as potential indicator of winegrape disease pressure under future climate change. This index was recently used for a similar purpose (Webb, 2006). The BI index is calculated as the sum of the products of monthly mean temperature and monthly rainfall. To be consistent with the derivations of other climatic indices presented in the Chapter 4, BI was calculated from October to April.

#### 6.2.1.4 Growing season moisture demand indicator

Vapour pressure deficit (VPD) is one of the key factors that determines the evaporative power of the atmosphere (Allen et al., 1998).The evaporative power of the atmosphere in conjunction with appropriate “crop” factors drives winegrape transpiration demand and it relates to irrigation requirement. Thus, for this study, average VPD during the growing season was examined as a potential irrigation requirement indicator. Growing season VPD is averaged from daily values of VPD. Daily VPD values were calculated as:

$$VPD = e_s - e_a$$

where, $e_s$ is the saturated vapour pressure, and $e_a$ the actual vapour pressure in the air. There are several methods to calculate the $e_s$. For this study, simple formula recommended by World Meteorological Organization (WMO, 2006) was used to compute the $e_s$:

$$e_s(T)=6.112\ e^{17.62\ T/(243.12+T)}$$

where, $T$ is the mean daily temperature (°C). Daily values of $e_a$ were obtained from global climate model outputs and downscaled to fine resolution (see Chapter 4).

### 6.2.2 Spatial data analysis

The level of spatial resolution represented by a pixel size in a raster map is of great importance in detailed spatial analysis. The resolution of the downscaled climate data used for previous chapters of this thesis was about 0.05 decimal degrees. In order to construct a more detailed spatial analysis for this study, the original resolution was further reduced to a 0.005 decimal degree resolution by re-interpolating the initial climate data in ArcGIS9.3 Geographic information systems (GIS) package (ESRI, Redlands, CA). By doing this, the resultant raster map pixel sizes were reduced to about 0.5 km, but at the expense of some data loss by the smoothing. However, the maximum differences between the pre- and post-interpolations were small. For example, preliminary results indicated a maximum difference of 0.04°C between the original and interpolated average GST in hilly areas. Interpolated raster surfaces of the climate variables were re-classified into their different classes, and subsequently converted into feature data sets in GIS. Areas under each climate category were obtained from the feature datasets.

## 6.3 Results

### 6.3.1 Changes in average GST conditions for WA wine regions

Currently warm L (17 to 18°C), warm H (18 to 19°C), and hot L (19 to 20°C) GST categories dominate the WA wine regions and occupy about 39%, 26%, and 18% of the total land area. Under the future climate change projections considered here, we model considerable shifts in these categories and proportions will likely to occur across the wine regions such that the areas under the cooler GST categories will likely decline while those under the warmer categories will likely increase (Table 6.2). Under low warming range, the warm H category will likely be dominant among the regions occupying 52%, 46%, and 37% of the total area by 2030, 2050, and 2070, respectively (Table 6.2). The area of land under the GST categories will potentially change at a faster rate under high warming condition. About 48% of the total area is projected to be under the hot L category by 2030, but by 2070 about 62% of the total area is likely to be under the very hot L category while over one-fifth of the area will potentialy become unsuitable for premium wine production (Table 6.2).

Table 6.2 Percentage of land area under average growing season temperature (GST) categories for Western Australian wine regions under SRES A2 emission scenario

| | GST categories | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Climate projections | Intermediate | Warm L | Warm H | Hot L | Hot H | Very hot L | Very hot H | Unsuitable |
| Base 1990 | 0.1 | 39.0 | 25.7 | 17.5 | 8.0 | 9.7 | | |
| MEDRES Miroc3.2 2030 | | 7.0 | 51.9 | 16.2 | 11.3 | 13.6 | | |
| MEDRES Miroc3.2 2050 | | | 45.8 | 20.9 | 14.3 | 17.1 | 1.5 | |
| MEDRES Miroc3.2 2070 | | | 37.1 | 26.2 | 15.3 | 14.9 | 6.5 | |
| CSIRO Mk3.5 2030 | | | 12.3 | 48.1 | 12.3 | 16.4 | 10.8 | |
| CSIRO Mk3.5 2050 | | | | 4.4 | 54.9 | 17.3 | 13.6 | 9.8 |
| CSIRO Mk3.5 2070 | | | | | 0.9 | 61.5 | 15.6 | 22.0 |

Ranges for GST categories: Intermediate 16-17°C, Warm L 17 to 18°C, Warm H 18 to 19°C, Hot L 19 to 20°C, Hot H 20 to 21°C, Very Hot L 21 to 22.5°C, Very Hot H 22.5 to 24°C, Unsuitable >24°C

Changes in the GST categories due to climate change will likely vary markedly from region to region. For example, currently almost the entire area of the Swan District falls under the very hot L category (Figure 6.1a; Figure 6.2a). Under low warming range, the very hot H category might cover about 20% of that region by 2050, and over 80% by 2070. Under high warming

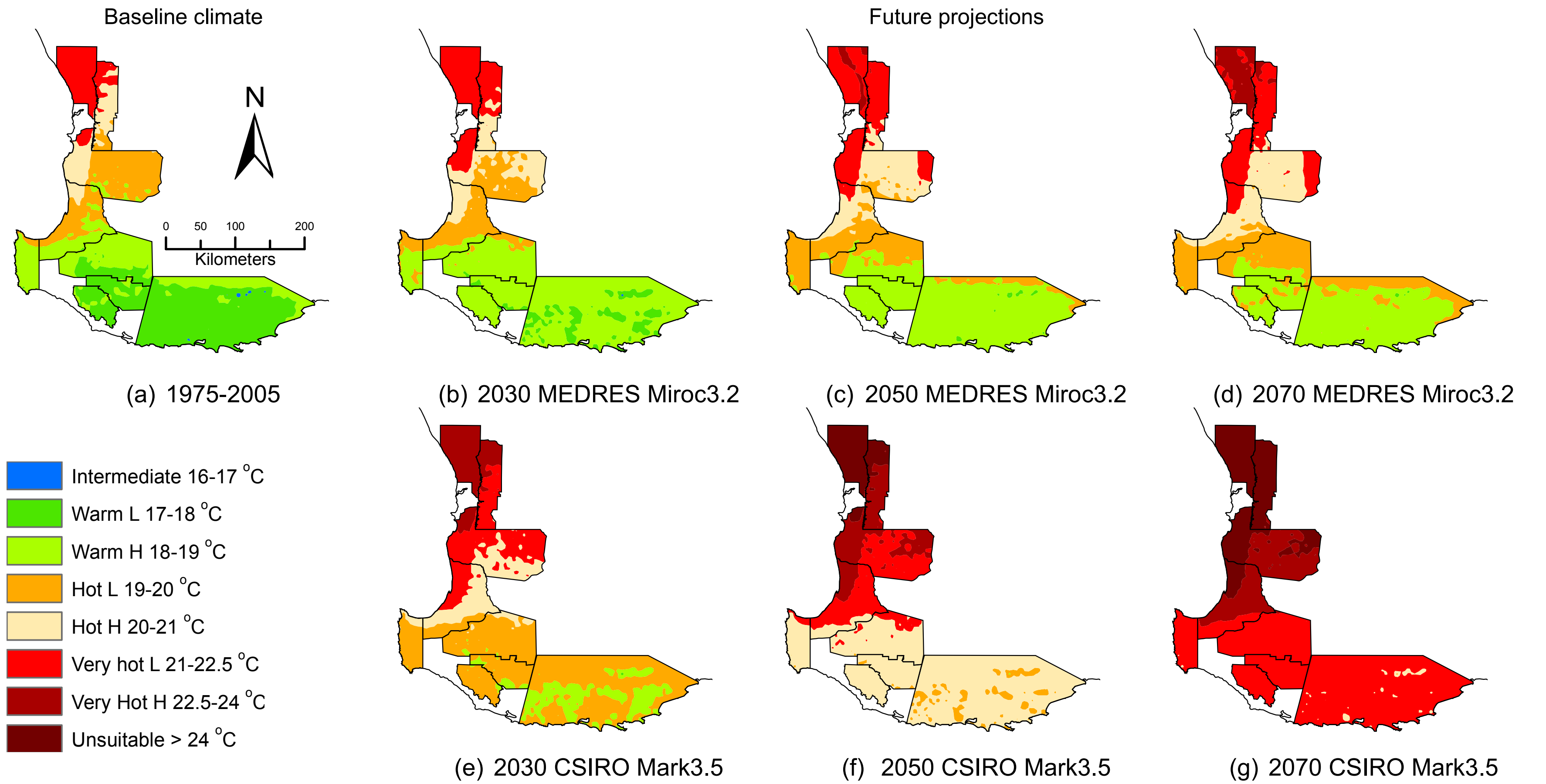


Figure 6.1 Spatial distributions of growing season temperature categories under current and projected climate under SRES A2 emission scenario

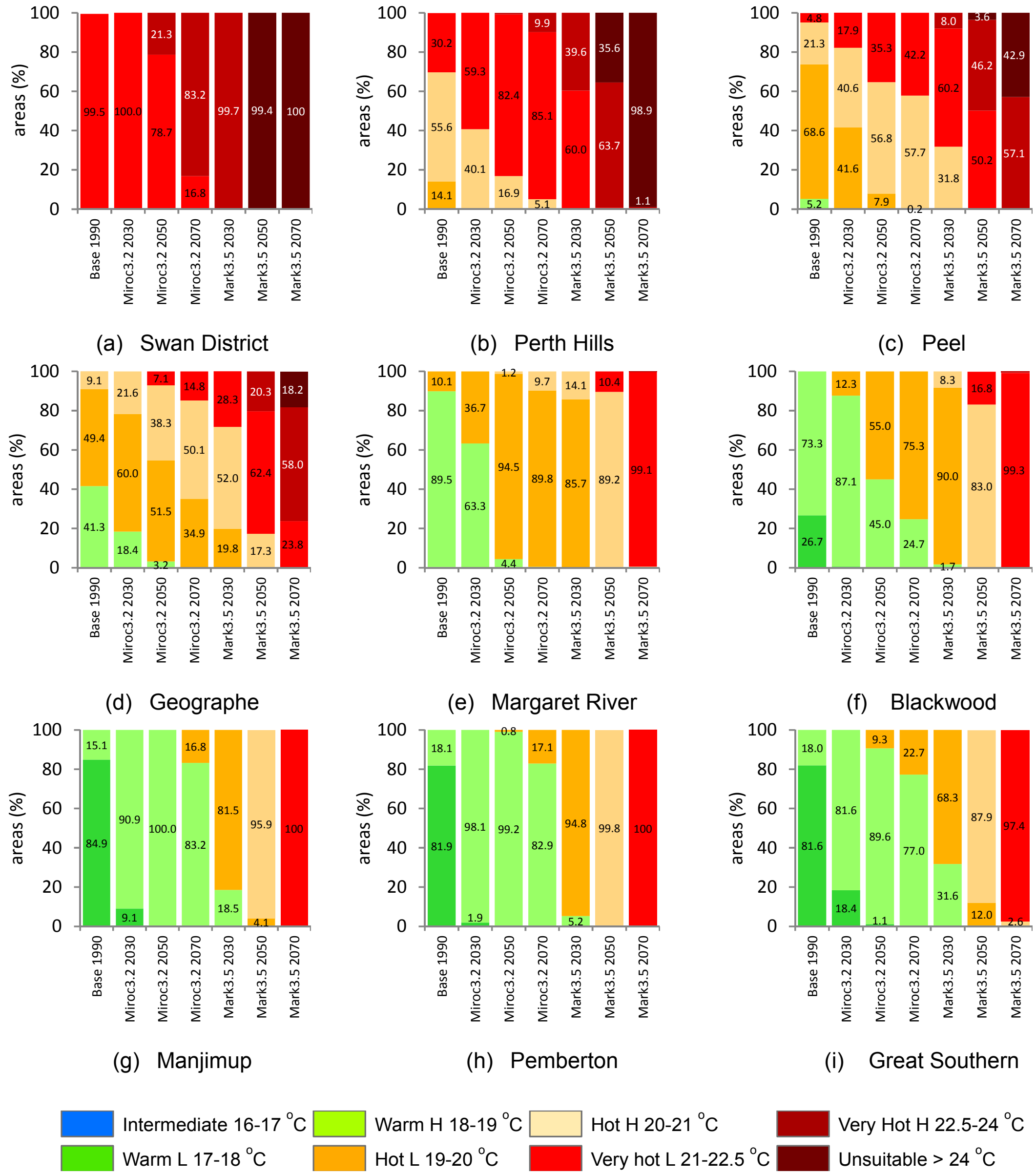


Figure 6.2 Changes in areas with different growing season temperature categories under current and projected climate under A2 emission scenario. Numbers in bars indicate percentage of area under that category

range, the entire area of the Swan District will likely fall under the very hot H category by 2030. By 2050 the entire district potentially be unsuitable for premium wine production as the average GST is projected to be over 24°C (Figure 6.1a; Figure 6.2a). One-third of the Perth Hills region is projected to be unsuitable for premium wine production by 2050, and the whole region by

2070 (Figures 6.1 f,g and 6.2b). Likewise, 43% of Peel and 18% of the Geographe wine regions are projected to be outside the premium wine growing GST category by 2070, if the high warming range is realised.

The smallest changes in the warm average GST categories are projected to occur in the southern regions. The currently prevailing warm L GST category is projected to be changed to a warm H category for the Manjimup, Pemberton and the Great Southern wine regions under low warming climate change range (Figure 6.1; Figure 6.2). Simultaneously and by contrast, gradual warming in GST is projected to convert the entire area of the Margaret River region, and about 75% of the Blackwood Valley region to the hot L category by 2070, from the currently dominant warm H category (Figure 6.1; Figure 6.2). Under high warming range, the changes in the GST categories will likely be more rapid. By 2070, the very hot L GST category is projected to prevail for all regions between Margaret River and the Great Southern (Figure 6.1; Figure 6.2).

### 6.3.2 Frequency of chill days during the winter season

The patterns of changes in chill days under future climate projection are similar for both high and low warming, but the magnitude is less under high warming range (Figure 6.3). The largest reductions in chill days are projected for the northern parts of the Great Southern region under both low and high warming ranges, dropping to 50 and 30 days, respectively, from the current 70 days, by 2070. Currently about 4% of the Margaret River region has less than 10 chilling days, but this area is projected to increase in the future to cover about half of the region under low warming range, and the entire region under high warming range by 2070. The western parts of the Swan District, Peel, and coastal areas of the Pemberton and Great Southern regions are projected to have 1 to 10 days of chilling under high warming climate change range (Figure 6.3; Figure 6.4).

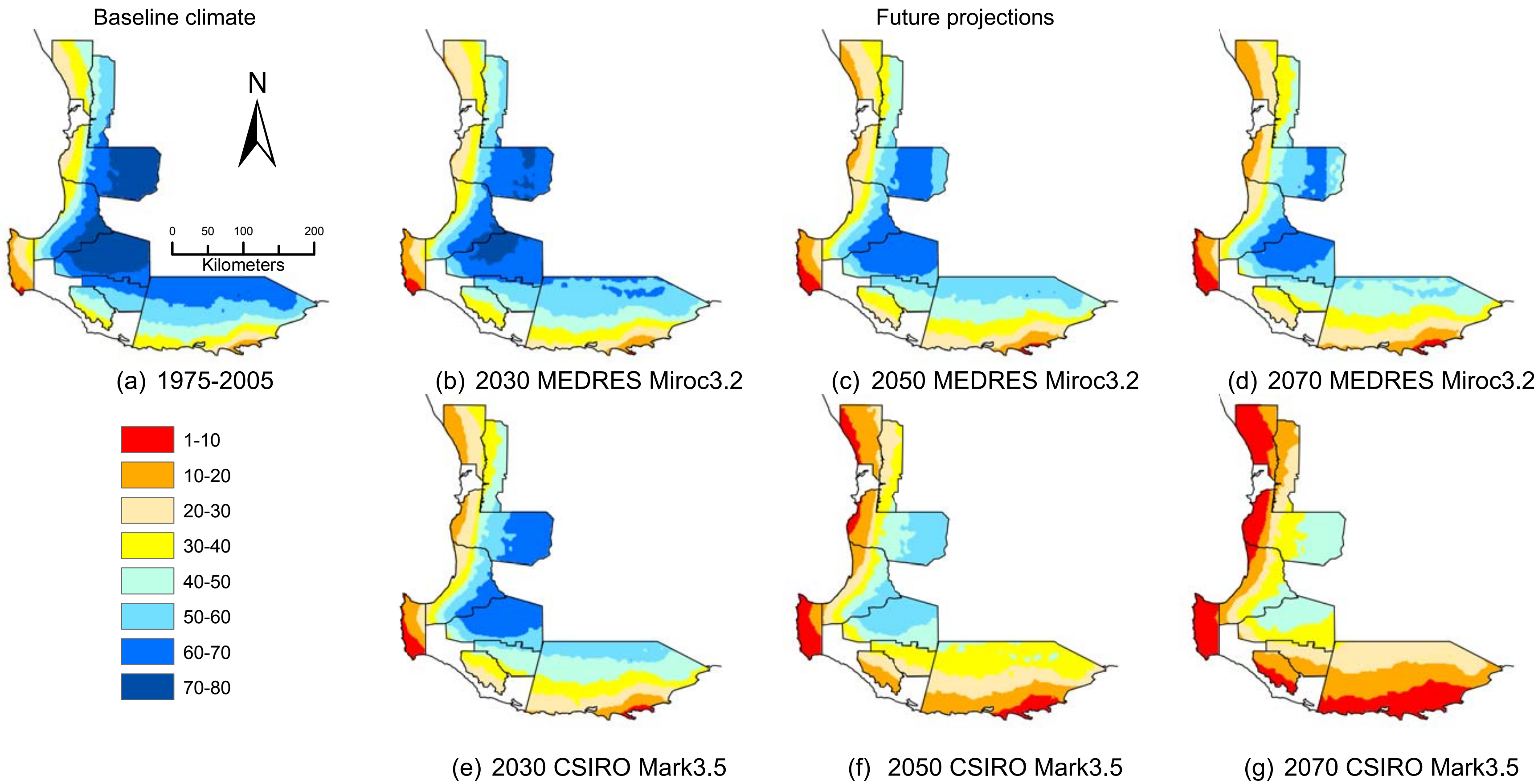


Figure 6.3 Spatial distributions of number of days with minimum temperature below 8°C during June to August under current and projected climate under SRES A2 emission scenario (in Days)

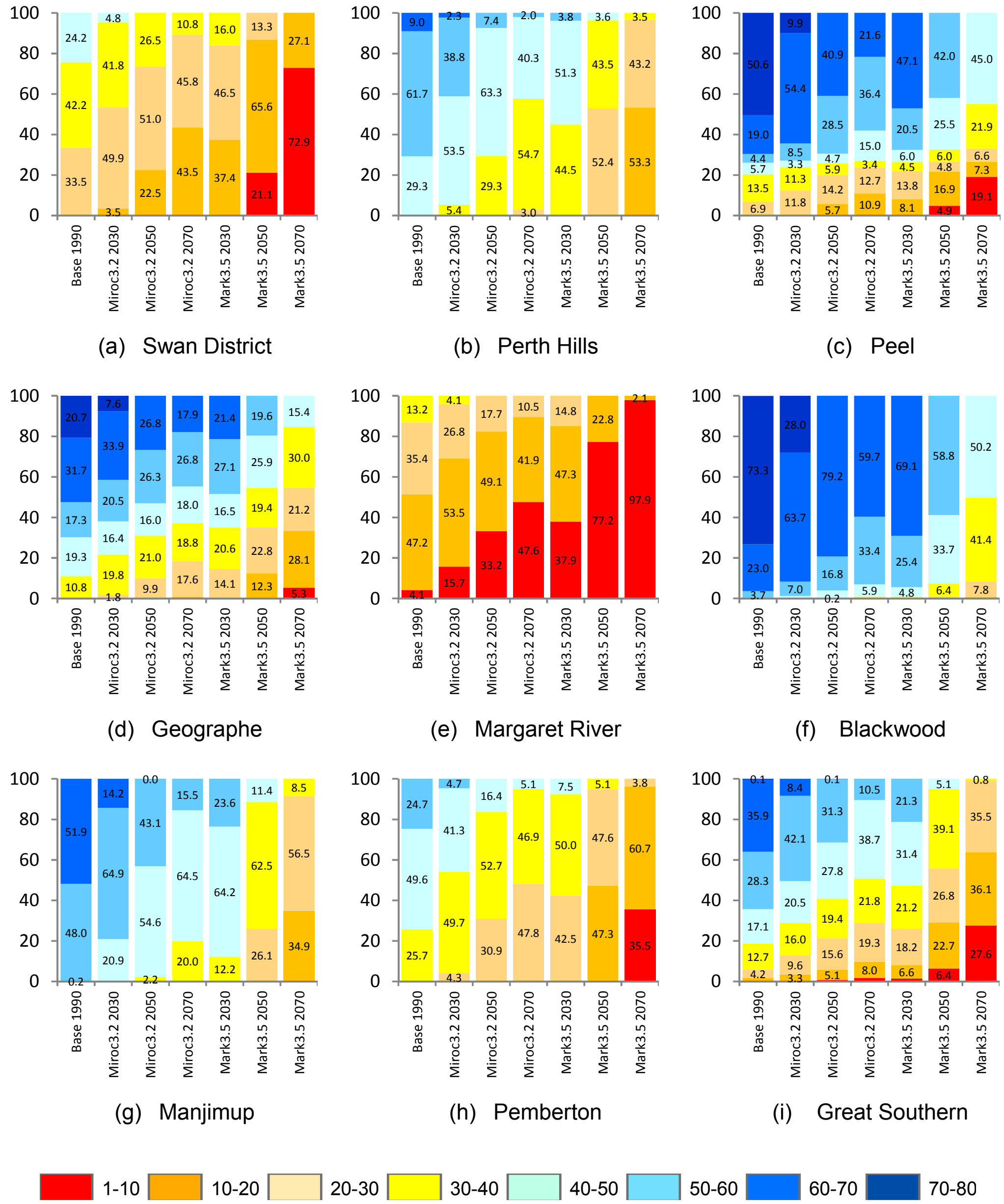


Figure 6.4 Changes in areas under different number of days with minimum temperature below 8°C under current and projected climate. Numbers in bars indicate percentage of area under that class under SRES A2 emission scenario (in Days)

### 6.3.3 Disease pressure

Currently, the southwest corner of the Great Southern region has the highest BI index of up to 6600 units among the study regions. The lowest BI regions are the northern part of the Swan District, and the farther inland parts of Peel, Geographe and Great Southern regions having 2600 to 3000 units of BI (Figure 6.5). Under climate change, areas with currently higher BI indices are projected to decrease, while areas with lower BI indices will likely increase across the wine regions studied (Figure 6.6). The greatest decreases in BI are projected to occur in some parts of the northern Swan District by 1200 units, whilst the southwest of the Great Southern region is projected to have up to 800 units less BI under high warming climate change range by 2070, when compared to the current climate. For example, currently a BI index range of 2600 to 3000 occupies about 57% of the Swan District, but it is projected to increase up to 65% by 2070 under low warming, whilst the majority of the area (64%) is projected to be in lower, 1800 to 2200, BI range under high warming range (Figure 6.6).

### 6.3.4 Moisture stress

The winegrape growing season average VPD currently ranges from 0.4 kPa in the southern regions to 1.2 kPa in the northern regions. The current distribution of VPD is projected to shift southward, but the magnitude of change will vary between the climate warming ranges (Figure 6.7). For instance, the maximum increase in the growing season VPD is projected to be 0.2 kPa under low warming range whereas up to 1.0 kPa of VPD increases are projected in northern parts of the Swan District and Perth Hills regions by 2070 under high warming range (Figure 6.7). Overall, current areas with low VPD range are projected to decrease, while high VPD areas are projected to dominate under climate change (Figure 6.8). The spatial distribution of areas of higher VPD range is projected to increase more for the northern regions under high warming range than for the southern regions (Figure 6.8)

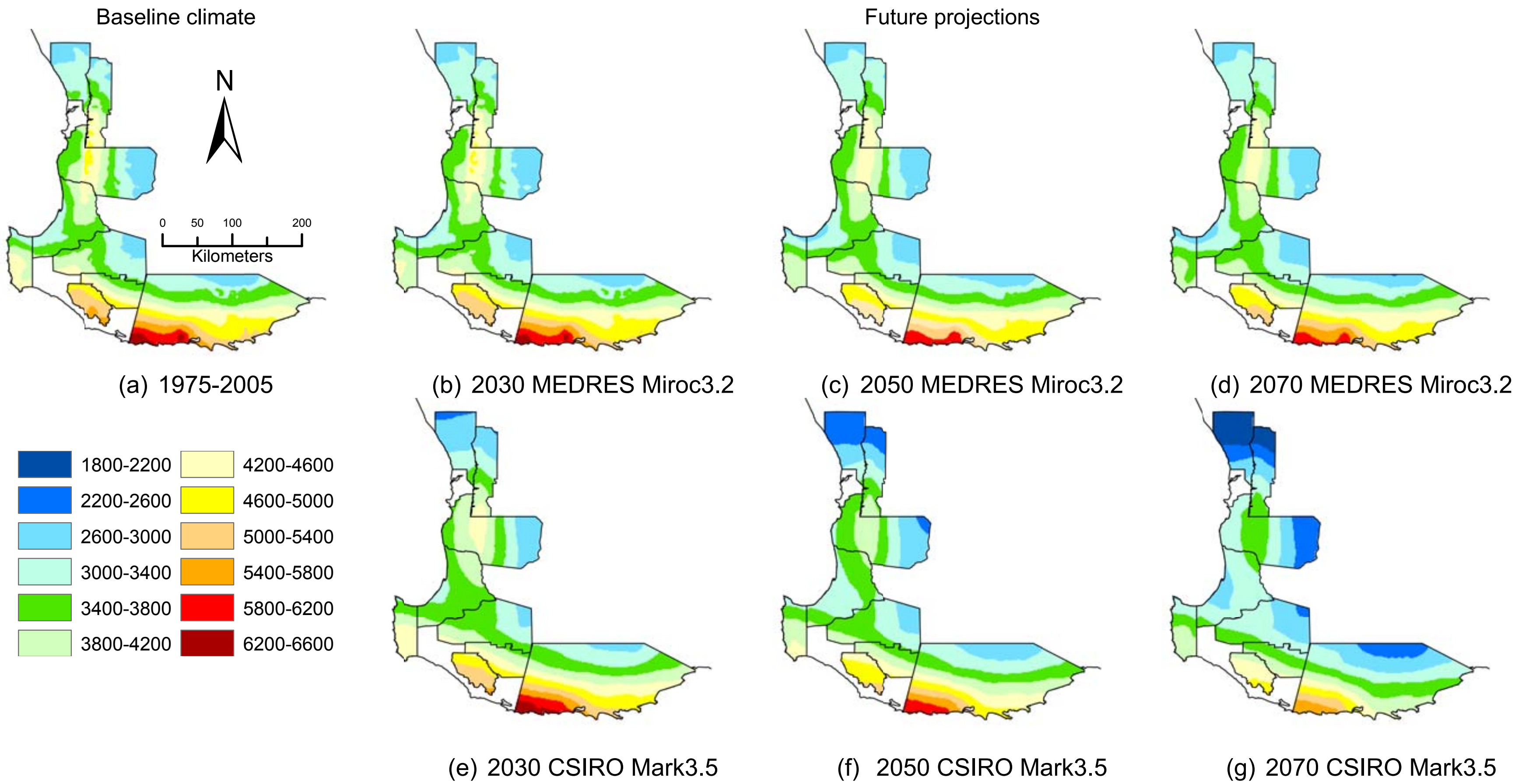


Figure 6.5 Current and projected Branas index during October to April under SRES A2 emission scenario (°C mm units)

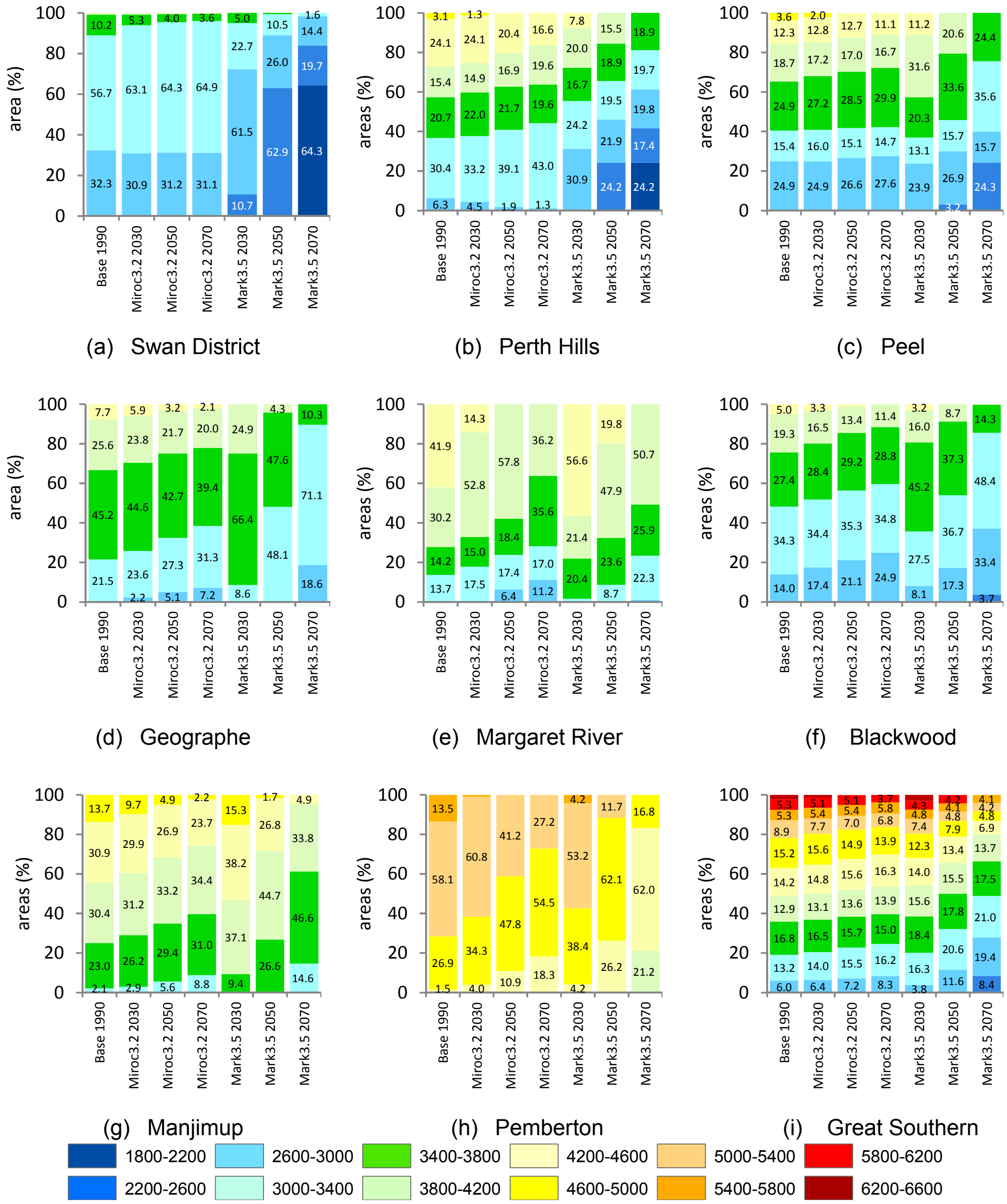


Figure 6.6 Projected changes in areas with different Branas Index class during October to April. Numbers in bars indicate percentage of area under that class under SRES A2 emission scenario (°Cmm)

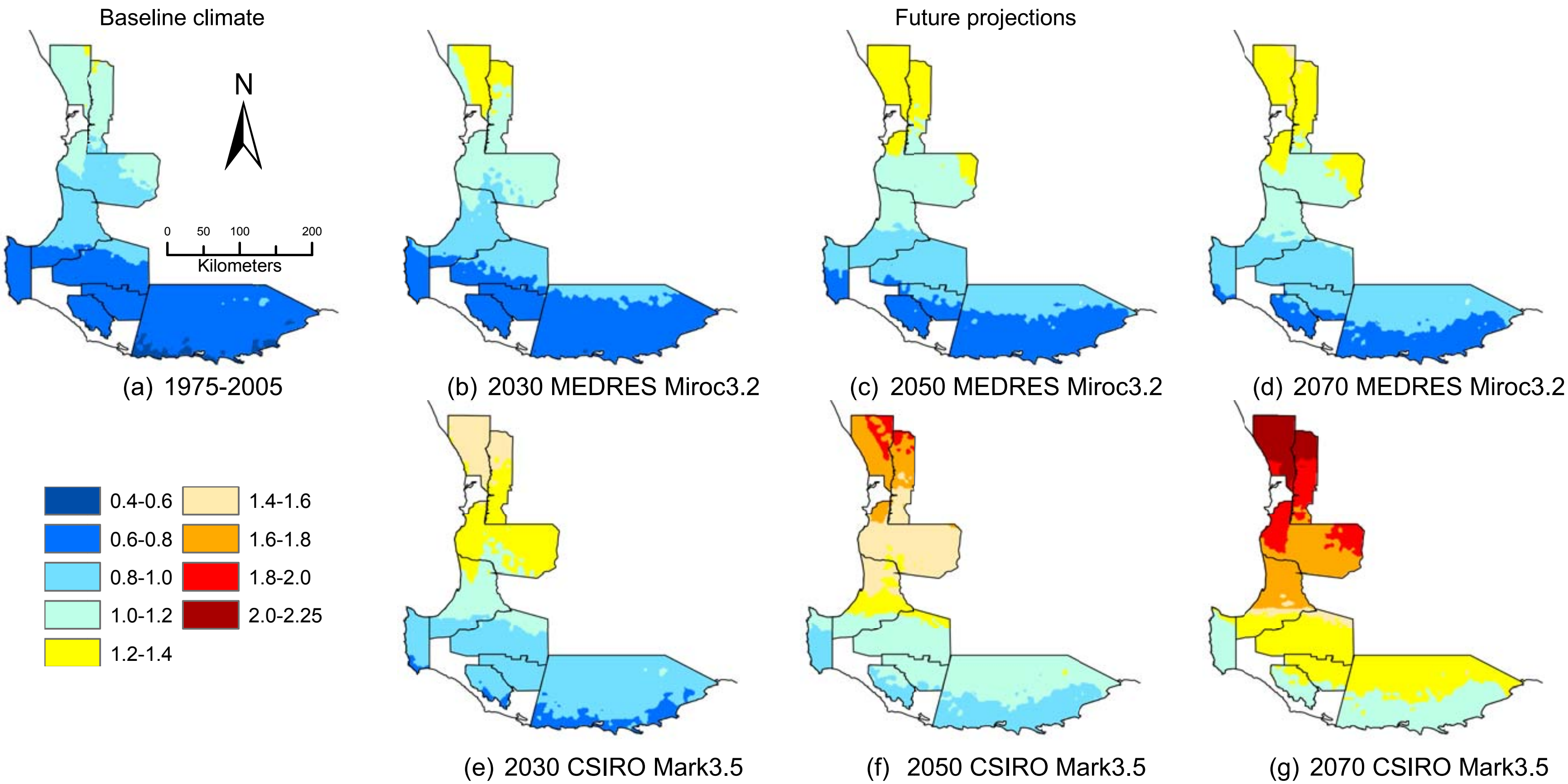


Figure 6.7 Current and projected VPD during October to April under SRES A2 emission scenario (kPa)

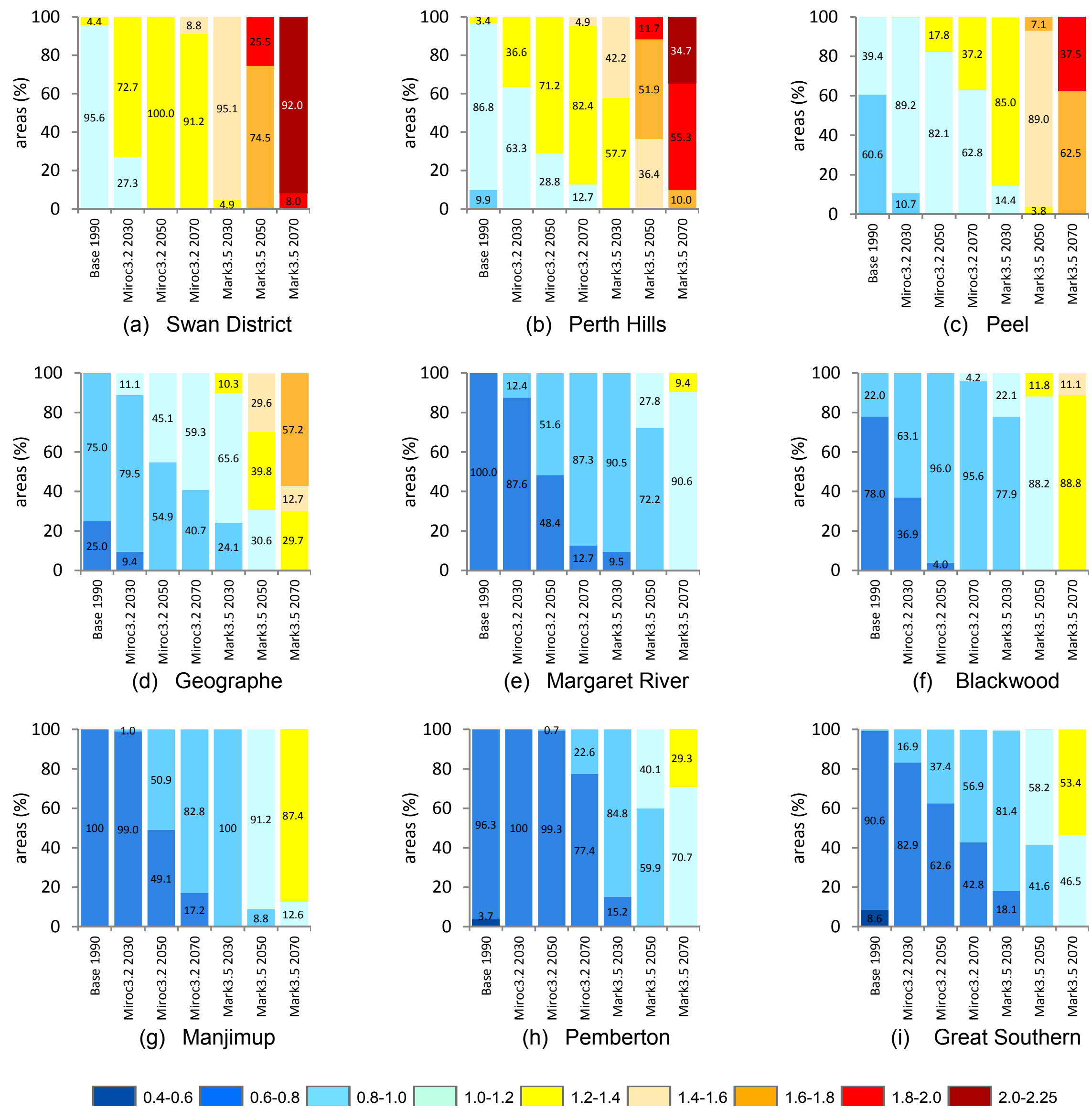

Figure 6.8 Projected changes in area with different vapour pressure deficit during October to April. Numbers in bars indicate percentage of area under that class under SRES A2 emission scenario (kPa)

## 6.4 Discussion

For this study, average GST was used as the main climate indicator for production of premium quality wines. In addition, the number of days under 8°C during the winter months, the Branas index, and the VPD during growing season were investigated as indicators of climatic limitations on vineyard management under climate change for WA wine regions. However, the risks associated with these stress variables for viticulture are not easily quantifiable. Therefore, throughout this chapter, the risks or stresses on winegrape growth and management under future climate are discussed in comparison with the conditions of those factors under current climate.

### 6.5.1 Trends in GST and implications for Western Australian viticulture

All of the WA wine regions are projected to have warmer winegrape growing season conditions under projected climate change. For example, under low warming climate change range, over 80% of the Swan District is projcetd to have a very hot (22.5-24°C) average GST by 2050, but the GST is projected to be even hotter under high warming range, assigning the whole region to the very hot category by 2030, and becoming less suitable (GST >24°C) for premium quality wines by 2050. Similar patterns are projected for the Perth Hills, Peel and parts of the Geographe regions (Figure 6.1 and 6.2). Under low warming range, entire areas of the Margaret River region and 75% of the Blackwood Valley wine region are likely to shift to a hot GST category (19°C to 20°C) by 2070, from their currently dominant warm category suggesting possible changes in wine style suiting a hot climate. Findings of this study is supported by the previous reports (Hall and Jones, 2009).

The potential impacts of climate change on the average GST distribution may have significant implications for WA viticulture in terms of varietal suitability or wine styles as winegrape quality attributes are defined by the prevailing climate in which they grow. With high warming range, all regions from the Margaret River to the Great Southern will likely shift to the very hot (21°C to 22.5°C) GST category by 2070. To put this in a simple perspective, the very hot GST category projected for these regions by 2070, is equivalent to the

GST prevalent for the western part of the Peel and the entire areas of Swan District under the current climate. According to Wine Australia (2011), under the current climate, the main varieties proven successful in Swan District are Chenin Blanc, Verdelho and Chardonnay, whereas in the Great Southern region Chardonnay, Riesling, Cabernet Sauvignon, Pinot Noir, and Shiraz are grown successfully. It is apparent that there is little overlap in the variety mix of these two regions. It is thus conceivable that in the future, the make up of varieties grown in the Great Southern will likely to mirror those of the Swan District with the attendant changes such a shift entails for regional character and so on. Therefore, the future warming will likely require grape growers in the WA to take adaptive measures to deal with the warmer climate to maintain their current market position.

According to Jones (2007), the upper limit of average GSTs for premium wine production is limited to about 20°C, while table grapes tolerate a warmer GST of up to 24°C. In practice, winegrape cultivation is not bound by these GST temperature limits, however, the existing literature for Australian viticulture suggests that, in general, the quality of grapes, and thus wines is inversely related to temperature, provided it is not limiting the ripening of grape (Gladstones, 1992, Coombe and Iland, 2004, Sadras et al., 2007c, Webb et al., 2008b). The findings of this study also indicate that the northern wine regions of WA may fall under a too hot GST regime unfavourable for quality wine production and this finding is supported by other studies that report similar results based on climate change impacts on a national scale (Hall and Jones, 2009).

### 6.5.2 Potential impacts of declining chilling days

Sufficient chilling helps uniform budburst within a shorter time period (Kliewer and Soleimani, 1972, Dokoozlian, 1999) minimising variation in subsequent phenological phases, yield and fruit maturity. An inadequate fulfilment of the chilling requirement is a particular concern for regions with mild winter temperatures and future warming may exacerbate it. It has been reported that the Margaret River region might experience later bud break due to an inadequate chilling requirement under climate change (Webb et al., 2007). This is reinforced by our results that indicate 48% to 98% of the land areas of the Margaret River wine region are projected to experience 10 or fewer days of 8°C by 2070, respectively under high and low warming climate warming range. Similarly, some areas (with close proximity to the coast) of the Swan District (73%), Peel (19%), Pemberton (35%), and the Great Southern (28%) wine regions are projected to experience 10 or fewer number of chill days from the current 20 to 40 days by 2070 if high warming climate change range occurs. Delayed and uneven budburst are likely to be problem in these areas unless dormancy management tools are employed.

### 6.5.3 Disease pressure

Diseases such as downy mildew and powdery mildew are high common fungal diseases in Australia and in WA wine regions (Emmett et al., 1992, Fisher and Wicks, 2003). Increases in temperature and humidity provide for favourable conditions for these diseases (Nicholas et al., 1994). Under both the low and high warming climate change ranges, areas of currently higher BI range decrease while areas of lower BI range increase, indicating reduced disease pressure across the WA wine regions. The reduced BI across the study regions appears to be due to the relatively high decline in rainfall compared to the increase in temperature across the wine regions. In terms of magnitude, the biggest decreases in BI are projected to occur in the northern Swan District, from the current 2600-3000 units to 1800-2200 units and in the southwest of the Great Southern region, from the current levels of 6200-6600 units to 5400-5800 units, by 2070 under high warming range (Figure 6.5).

Some wine regions of Australia are reported to have even higher BI, for example 8500 for Hunter Valley between the October to March period (Webb, 2006) under the current climate. Webb also suggested possible reduced disease pressure for Margaret River region under climate change. Findings of this study is in agreement with above statement (Figure 6.6). The reduced BI across the wine regions potentially implies lower management costs of monitoring, and spraying to deal with fungal disease, provided other conditions are not conducive for disease development. However, as suggested by Chakraborty et al. (1998) potential increases in canopy growth triggered by elevated atmospheric $CO_2$ levels may also increase disease pressure at microclimate level.

### 6.5.4 Trends in VPD and its implications

The growing season VPD is projected to increase under climate change across the study regions, together with areas under a higher VPD range. While the increases in VPD under low warming condition are minimal (<= 0.2 kPa), increases of up to 125% (1.05 kPa) are projected under high warming condition in some localities of the northern wine regions. The area that experiences 2 to 2.25 kPa VPD under high warming condition is projected to be 92% and 35%, respectively for the Swan District and Perth Hills regions by 2070 (Figure 6.7). This amount of increase in growing season VPD can be consequential.

The increases in VPD and its spread for WA wine regions have at least two major implications: 1) increased irrigation demand during the winegrape growing season, and 2) reduction in grape berry quality. More water is transpired from the plant to the air when VPD is high (Prenger and Ling, 2002). The increased demand for irrigation during the winegrape growing season might create serious challenges across WA wine regions as the regions are projected to experience decreased rainfall under climate change (Chapter 4). For example, growing season VPD (currently between 0.4 to 0.8 kPa) in the Great Southern region is projcetd to increase by up to 0.6 kPa, while the region will likely experience drier (35% reductions in median growing season rainfall) growing conditions under high warming range by 2070. In addition, higher VPD could cause elevated levels of pH in grape berries due to increased potassium uptake from soil through increased transpiration, and higher levels of pH in grapes and wines are associated with inferior wine quality (Rankine, 1989).

## 6.6 Conclusion

This study examined future winegrape growing conditions in WA wine regions utilising average GST as the main indicator of premium quality wine production, with additional indicators for winegrape chilling requirement, conditions of disease pressure, and vapour pressure deficits under climate change. If future climate change develops under high warming climate change range of this study, entire areas of the Swan District, Perth Hills, and parts of the Peel (43%), and Geographe (18%) regions are projected to be less suitable (GST >24°C) for premium quality wine production in the next 60 years. Planting table grape or making fortified wines may become suitable options for viticulture in the above regions.

The cooler southern wine regions are projected to have the GST conditions currently experienced by the warmer Swan District. Changes in the growing season conditions are less pronounced under low warming climate change condition in this study, however, major areas of three wine regions (Perth Hills, Margaret River and Blackwood Valley) are projected to shift to a warmer category of GST, requiring the industry to adapt to the new climatic environment. Therefore, significant challenges relating to changes in varieties suited to warmer climate space or adaptation of management options to cope with the impacts of warmer conditions will potentially become reality for WA viticulture under climate change.

All regions are projected to have a less number of chilling days during what should be a dormancy period, and the areas under a low number of the chilling days will be increased. Fungal disease pressure is likely to decline in all regions benefiting the growers by reduced disease management costs. However, the projected increases in VPD during the growing season will likely create extra pressure for growers to meet the increased irrigation demand, and this will likely be even more challenging since rainfall is projected to decrease across the regions. Collectively, the above findings suggest that future climate change will likely be challenging for WA wine regions if appropriate adaptation strategies are not implemented.

# CHAPTER 7. GENERAL DISCUSSION

## 7.1 Introduction

Climate exerts a strong influence on winegrape development and grape quality and, hence, changes in future climate are likely to impact on viticulture. This thesis research was aimed at carrying out climate change impact assessment for key berry quality attributes (anthocyanins, TA and pH) across the Western Australian (WA) winegrape producing regions. To achieve this overarching aim, the following key component aims were realised in this thesis project:

1. Empirical models that relate key berry quality attributes to climate variables were formulated for the major winegrape varieties in WA,

2. Fine spatial resolution climate surfaces were constructed for the WA wine regions for 2030, 2050 and 2070.

3. Berry quality attribute surfaces (anthocyanin concentrations, titratable acidity, and pH) of Cabernet Sauvignon, Shiraz, and Chardonnay varieties were modelled across the WA wine regions under low and high warming climate change ranges. To our knowledge no other studies have projected direct grape quality attributes under climate change at regional scale in Australia or elsewhere.
4. Furthermore, analyses of future climate conditions for premium wine production for the WA wine regions were carried out.

This final chapter discusses and synthesises the findings of this study. It also addresses contributions of this work and identifies future research into climate change impacts on viticulture based on the outcomes of this study.

## 7.2 Climate and grape quality attribute relationships

Qualitative descriptions of climate influence on berry quality abound although quantitative translations of such descriptions are relatively scarce. On the other hand, a fuller assessment of climate (change) impacts on berry quality precisely requires quantitative models that are formulated ideally from directly measured climate and berry quality data. Generation of such data however is difficult. Some options, each with its own limitation, include carrying out a range of controlled climate experiments or sampling along natural gradients of climate. The controlled climate option, apart from being expensive, has the inherent difficulty of replicating vineyard conditions while the climate gradient potentially incorporates gradients in non-climatic factors. In this thesis, the gradient study option was undertaken as a compromise approach towards providing a quantitative framework that describes berry quality as a function of climate variation.

In accord with the widely held view, the results from the climate-gradient transect study showed reduced anthocyanins and acidity, and increased pH in warmer sites compared to grapes from cooler sites. The sampling protocol devised in this project enabled such qualitative descriptions to be quantitatively formulated. Thus, in spite of the covariations of non-climatic factors along the sampling transect, when data are examined at a common maturity, empirical models incorporating only climatic factors explained most (~85%) of the variations in the levels of grape anthocyanins and TA, and half of the pH variability across sites. While at one level, these model results help to identify climate as having an overriding influence on berry quality, at another level the models have elucidated multilayered "interactions" that affect the levels of berry quality attributes. For instance, as detailed in Chapter 3, the specific climate components and the vine and/or berry developmental stages during which these exert significant (positive or negative) influence appear to differ among the berry quality attributes and to some extent among the winegrape varieties examined in this work. This can be illustrated by way of example: in Shiraz, berry anthocyanins concentrations were primarily influenced by January average or minimum temperatures whereas in Cabernet Sauvignon, in addition to the average January temperatures, rainfall was also a significant factor. Further, the direction of the rainfall effect can be positive if it occurs early in the growing season or detrimental if incident during the berry maturation period. Such insights may be useful as part of the "tool set" for devising informed adaptation strategies, e.g., when considering site selection, irrigation management or even perhaps in choosing which variety to plant at a given location. Moreover, the empirical models developed from this work were useful for quantitatively assessing magnitudes of likely quality changes due to climate change, at least for the wine regions and varieties covered in the this study. Once again, the models can be used as part of the tools for gauging risks in long term planning – such as whether the projected changes in berry quality levels would be tolerable or not. Results of this work also showed decreased accumulation rates of anthocyanins (significant for Cabernet Sauvignon) and declines in titratable acidity decline (significant for Chardonnay) per unit of total soluble solid (TSS) increase under warmer conditions (Chapter 3). This type of decoupling of TSS and grape quality attributes under warming conditions presents a challenge for production of wines with balanced quality attributes.

## 7.3 Future climate conditions for Western Australian wine growing regions

There is increasing evidence that the climate warming that has occurred to date is due to the elevation of greenhouse gas concentrations in the atmosphere (IPCC, 2007). Several studies have reported earlier phenological events, shortening of winegrape growing season, earlier maturity (Jones and Davis, 2000b, Duchêne and Schneider, 2005, Petrie and Sadras, 2008, Tomasi et al., 2011, Webb et al., 2011), and increased grape and wine quality (Nemani et al., 2001, Jones and Davis, 2000b) around the world due to the changes in climate to date. Impact assessments under future climate have also been carried out at varying scales, the results of which generally indicate potential opportunities and challenges from future climate change for viticulture depending on the current climate and future warming (Jones et al., 2005, Webb, 2006, Hall and Jones, 2009). This underscores, the need for detailed pictures of future climate (e.g., spatially as well as various components of climate). For viticulture – an industry that is based on a crop with a narrow climate niche for quality production – such information is critically important both to capture potential opportunities and to prepare for challenges of climate change in a given region. In consideration of this point, this project constructed detailed future climate surfaces for WA wine regions at fine scale since direct outputs of global climate models are of limited use for local or regional impact assessments due to their coarse spatial resolution (>110 km). Future climate conditions and derivative metrics, GST, MJT, ripening period temperature, and BEDD for Australian wine growing regions have been constructed at national scale utilizing CSIRO Mk3.0, HadCM3, and regional DARLAM climate models (Webb, 2006, Hall and Jones, 2009). This thesis has built upon these recent works and has generated a variety of temperature, rainfall and radiation (and their derivatives) indices at detailed spatial scales and three (forward) time frames across the WA wine regions.

For the WA wine regions, the overall picture of the future climate generated from this work shows increased temperature and heat accumulation, reduced rainfall and increasingly dry conditions which is broadly in accord with earlier findings (Hall and Jones, 2009, Webb, 2006). Growing season (October to April) and grape maturity period (February to March) temperatures are projected to increase by about 1.5°C to 4.5°C under the low and high warming ranges by 2070, respectively. Non-growing season (May to September) temperature is also projected to increase by up to 3°C by 2070. Growing season heat accumulation will likely be increased about 300 to 900 units, respectively under low and high warming, during growing season by 2070. The frequency of hot days is projected to increase by up to 80 days in the northern regions and 20 days in the southern regions by 2070 under high warming range. Such heat waves may necessitate increased irrigation application to mitigate potential negative impacts on berry quality (Chapter Three), yield and canopy physiological competence. This might become a critical limitation to viability of the industry for some water-limited regions such as the Great Southern.

Positive impacts of warming on viticulture could be increased amount of heat accumulation if the current region or a particular variety is limited by cold temperatures or lacking enough heat accumulation for ripening, for example, the cool climate viticulture in Canada (Caprio and Quamme, 2002, Shaw, 2005). However, this type of positive effect of warming seems less relevant for the WA wine regions, as nearly all the regions receive enough heat accumulation for the common winegrape varieties even under current climate conditions. Increased temperatures during grape ripening potentially imply unbalanced grape quality composition: decreased acidity and flavour components at given sugar levels, or too high sugar levels and low acidity when the flavour compounds reach optimal levels if the temperature is warmer than suitable for a particular variety to ripen (Jones, 2007). The negative relationships between temperature and berry quality (Chapter 3) and the projected increases in temperature (Chapter 4) for the WA wine regions indicate potential overall negative impacts of climate change on grape quality across the study wine regions.

Rainfall is projected to decrease across the WA wine regions under climate change under future scenarios selected for this study. Reductions in rainfall are projcetde to be more pronounced for spring rainfall for the Swan District (76%), Perth Hills (72%), and the Great Southern (65%) regions under high warming. Reduction in spring rainfall combined with the increasing temperature and vapour pressure deficit may force grape growers to start early irrigation and that alone will likely bring substantial challenges for some regions, for example, in the Great Southern where water supply is entirely dependent on rainfall and grape production is limited by water supply even under the current climate. Winter rainfall is also projected to reduce. Declines in winter rainfall will likely decrease the amount of water harvested from run-off catchments. Potential early start of irrigation, combined with less reserve water in dams, might create a serious water shortage situation later in the growing season, which is crucial for grape quality development as shown in Chapter 3.

## 7.4 Projected grape maturity and quality under climate change

Grape quality is the main determinant of wine quality when other factors such as wine making practices are similar. Yet, there are no studies that quantitatively assess climate change impacts on directly measured quality attributes of grape. To date studies of climate (change) effects on grape and wine quality used surrogate measures such as vintage ratings or price as indicators of quality. These indicators are useful for assessing climate influences for grape and wine quality based on historical relationships; however, these are prone to criticism due to their indirect link to objective measures of grape or wine quality. Empirical models linking grape quality with climate (Chapter 3) and climate projections (Chapter 4) enabled projections of key quality attributes of major winegrape varieties of WA wine regions. The fine resolution of the downscaled climate data allowed construction of grape quality surfaces such that not only inter-regional but also intra-regional differences could be evaluated quantitatively.

Grape quality reduction is projected to be higher in the warmer northern wine regions than in the southern districts. Results of this study suggest that relative reductions in current median Cabernet Sauvignon anthocyanin concentrations at common (22 °Brix total soluble solid) maturity will potentially be almost two fold (33%) higher for the northern districts by 2070, than the reductions (18%) in the cooler southern regions. Patterns of decline in median Shiraz anthocyanin levels are similar to that of Cabernet Sauvignon; however, the reduction is less, up to 18% and 11% respectively for the warmer and cooler regions by 2070 under high warming range.

Cabernet Sauvignon and Shiraz median TA levels are projected to drop by 12% and 15% by 2070 for the warmer Swan District and Peel regions compared to current levels under high warming range. In this study, Chardonnay median TA is projected to drop by as much as 42% in the warmer Swan District by 2070 under high warming climate change. The relative TA declines for the cooler southern regions are less for Chardonnay (~28%) and Cabernet Sauvignon (~4%), but similar Shiraz (14%) under high warming range. Impacts of low warming climate change range on median TA levels at common maturity were small with a maximum decline of 6% for Chardonnay for the Great Southern region by 2070.

Effects of decreasing berry anthocyanin concentrations and TA will likely be expressed in wine quality. Grape berry anthocyanin is formed in the vineyard;

therefore, it is unlikely that significant grape colour adjustments can be made at the winery level. On the other hand, reductions in berry acidity, can be adjusted by using acid additions during winemaking, but it will involve extra cost. Wines with added acidity will likely be of less quality compared with naturally balanced wines (Gladstones, 1992). Therefore, reductions in grape anthocyanin concentrations and acidity levels due to climate change potentially cause decreased wine quality, but the decline will largely depend on the magnitude of future warming.

Results of modelled winegrape maturity dates and grape quality indicate asymmetric advancement of grape maturity and uneven changes of winegrape quality across the WA wine regions due to climate change. Cabernet Sauvignon, Shiraz and Chardonnay maturity at 22 °Brix TSS maturity are projected to be 6 to 7 weeks earlier by 2070 in the cooler southern regions under high warming, while the same varieties will likely reach this maturity level about four weeks earlier in the warmer northern regions. These asymmetric changes; smaller in warmer regions and larger in cooler regions in grape maturity under climate change are in agreement with the modelling results by Hall and Jones (2009) despite differences between the models used.

## 7.5 Climate change impacts on premium wine producing conditions

Environmental conditions, climate, geology and topography, all contribute to the unique characteristics of wine style in a given region (terroir). Of the environmental conditions, climate is acknowledged as the most important determinant of winegrape growth and grape quality. It is thus probable that climate change might alter existing premium wine production and wine styles. Average growing season temperature was selected for this study as main metric for assessing suitability of climate for premium wine productions across the WA wine regions under climate change due to:

1. its common applications for similar studies in the past, and

2. its close relationships with other main climate variables defining the climate suitability for viticulture.

Additionally, other climatic conditions that can affect viticulture such as winegrape chilling requirements during dormancy (number of days with minimum temperature less than 8°C during dormancy), disease pressure (Branas index) and potential irrigation requirements (vapour pressure deficit) under climate change are examined to assess how the different regions will fare. Increases in the growing season temperature are likely to cause most of the regions to adopt warmer climate varieties, while some regions might be less suitable for producing premium quality wine. For example, by 2070 entire regions of Swan District, Perth Hills, and some parts of Peel (43%) and Geographe (18%) regions will likely be less suitable for premium wine production under high warming assumption in this assessment. Currently the Swan District, and northern parts of Perth Hills regions have average growing season temperature range of 21 to 22.5°C, but by 2070, this range is projected to cover entire areas of the Margaret River, southern parts of Geographe, Blackwood, Pemberton, Manjimup, and the Great Southern regions under the high warming scenario. Under the climate projections examined here, there is a clear indication of varietal suitability challenges for the currently planted varieties in those regions and the need of adapting to the changing climate.

The above findings are similar with other research reports that used different criteria to examine climate suitability for winegrape varieties under climate change. For example, Kenny and Harrison (1992) used latitude temperature index as climate suitability index for winegrape varieties and reported that some parts of Southern Europe may become unsuitable for some winegrape varieties due to temperature increase, while other areas in Eastern and Northern Europe may become viable for winegrape production due to climate change. It is also reported that premium wine producing areas of the USA will drop by up to 81% at end of this century due to combined effects of increasing temperature and heat accumulation, temperature variability and frequency of hot days with maximum temperature over 35°C (White et al., 2006).

Meantime, other factors brought about by climate change, such as decreasing occurrences of cold nights, and elevated vapour pressure deficit during the growing season, may force grape growers to take additional measures such as dormancy breakers or revised water management in accordance with the changing climate.

## 7.6 Contribution of this study to this field of research

This study provides spatially detailed projections of various climate variables across the WA wine regions for the next 60 years. Projections of climate variables which include temperature, rainfall, radiation, vapour pressure deficit at fine spatial resolutions could be useful for the industry to further develop a comprehensive understanding of climate change and its adaptive capacity across the studied wine regions. Projections for 2030 can be useful for the industry to incorporate adaptation strategies in their planning horizon, while 2050 and 2070 projections are useful for consideration of longer term potential impacts of climate change on viticulture. Projected grape quality attribute surfaces, which is new in this field of study, also provide a clear indication on the directions and magnitudes of climate change impacts on grape quality across the study regions in the near and distant future.

## 7.7 Future research

### 7.7.1 Modelling of winegrape phenology

Winegrape phenology is dynamic, it primarily depends on prevailing weather and the future warming is likely to alter it. Thus, use of calendar based climate variables for projecting winegrape response to future climate change is a clear limitation of this type of study. One of the possible ways of overcoming this problem is to develop parameterised models, either statistical or process based, that accurately predict the phenology under climate change.

### 7.7.2 Modelling of water balance

Increased temperatures and vapour pressure deficits across the WA wine regions are likely to drive irrigation demand higher, which creates extra pressure for growers with limited water supply for irrigation. As such, studies on water budget and irrigation demand under climate change are of great importance for some of the Western Australian wine regions, for example the Great Southern region, due to their dependency on rainfall, which is projected to reduce in the future. Such studies will help the wine industry to identify appropriate adaptations, such as improved water management, or new varieties with better water use efficiency, to future climate change.

## 7.8 Concluding remarks

As projected in this study, Cabernet Sauvignon, Shiraz, and Chardonnay maturities are projected to advance asymmetrically across the WA wine regions. Some of the current warmer northern regions in WA may no longer be suitable for producing premium quality wines under climate change. The currently, cool southern regions are projected to have the growing season temperature condition that are currently predominant for the warmest northern regions indicating substantial challenges for managing current varieties or need for changing to warmer climate varieties. Moreover, grape quality attributes, colour and acidity, of dominant winegrape varieties for the WA wine regions are likely to decrease under climate change. Taken together these findings indicate increased pressure from climate change on WA viticulture, but the extent will be heavily dependent on the degree of the future climate change.

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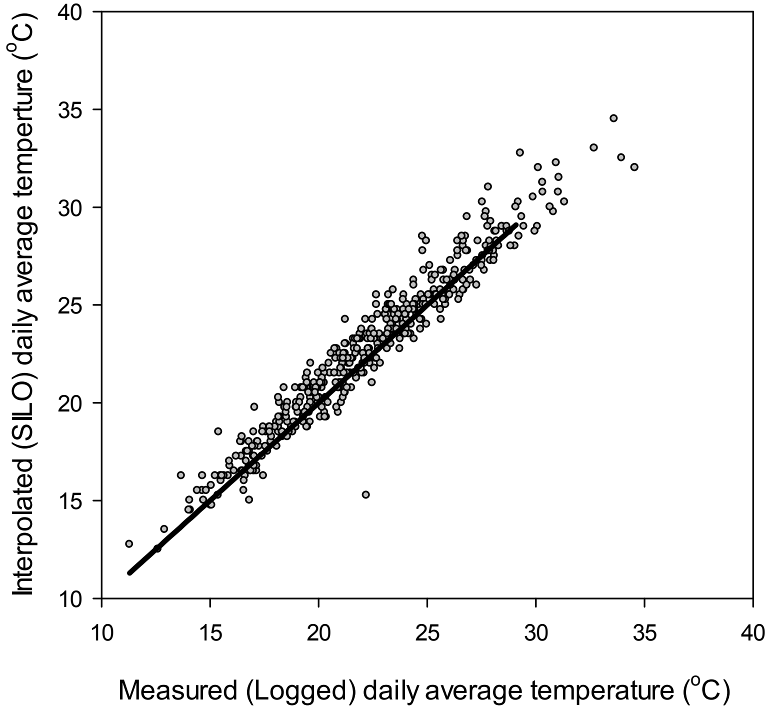
## APPENDICES

Appendix 1. Relationships between measured (logged) and interpolated temperatures. Stright line represents 1=1 situation where each measured and interpolated temperatures matches. This pattern is maintained across all different sites, but this graphs shows Peel and Pemberton sites data as an example..

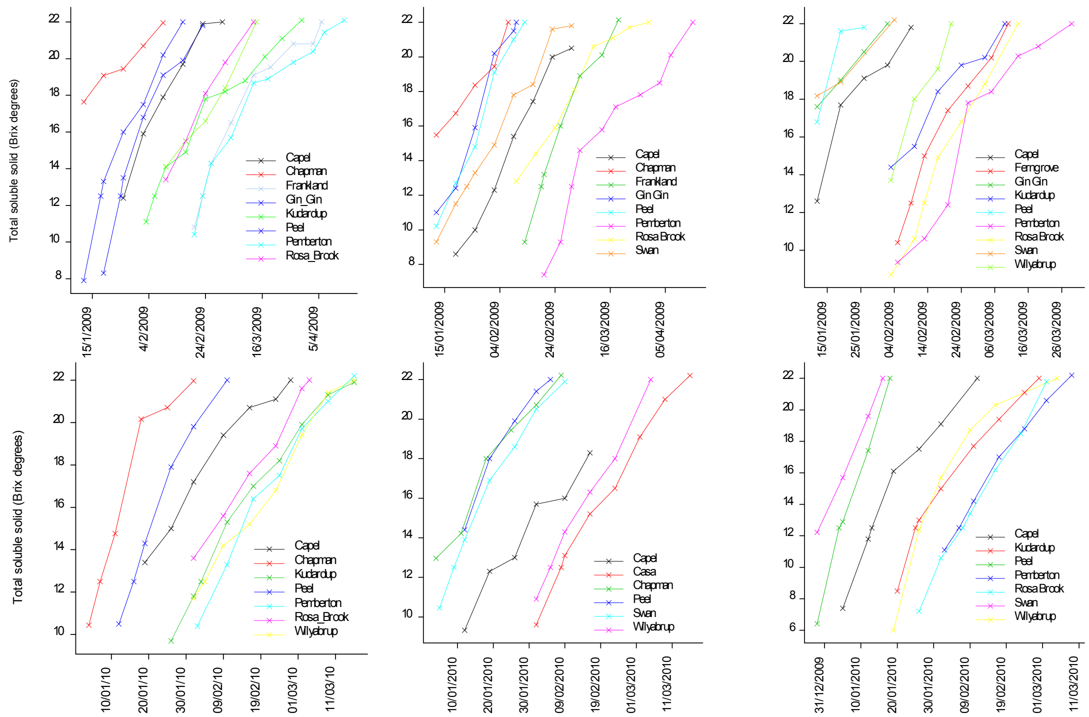


Appendix 2. Changes in grape quality attributes during véraison at the sampling sites

Cabernet Sauvignon | Shiraz | Chardonnay

Season 1
(2008 to 2009)

Season 2
(2009 to 2010)



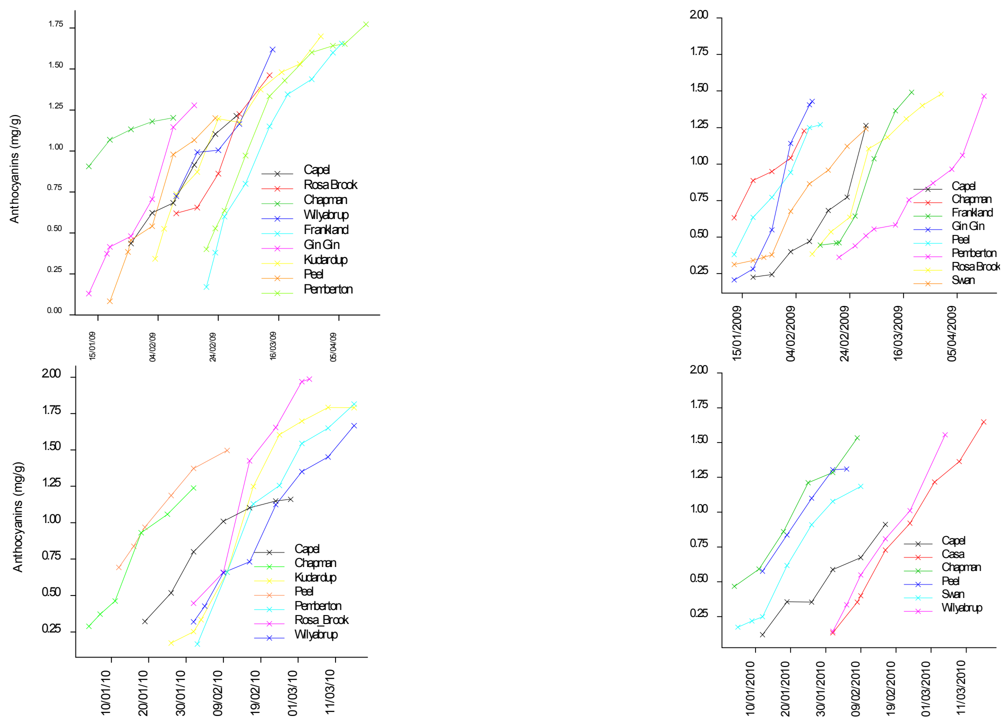

Accumulation of total soluble solids up to a maturity of 22.0 °Brix during véraison for Cabernet Sauvignon, Shiraz, and Chardonnay. Sampling sites were represented by the names of the localities along a natural climate gradient in Western Australia.

Cabernet Sauvignon anthocyanin

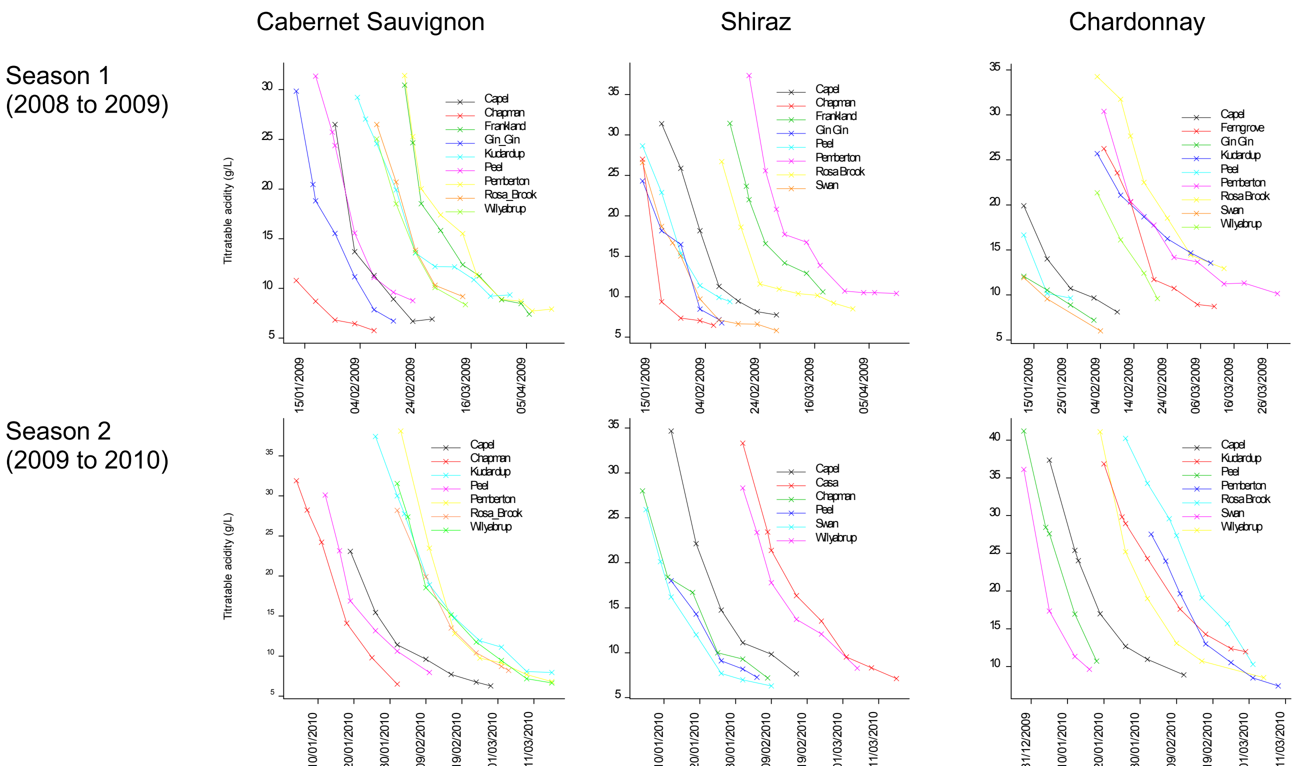
Shiraz anthocyanin concentrations (mg/g) concentrations (mg/g)

Season 1
(2008 to 2009)

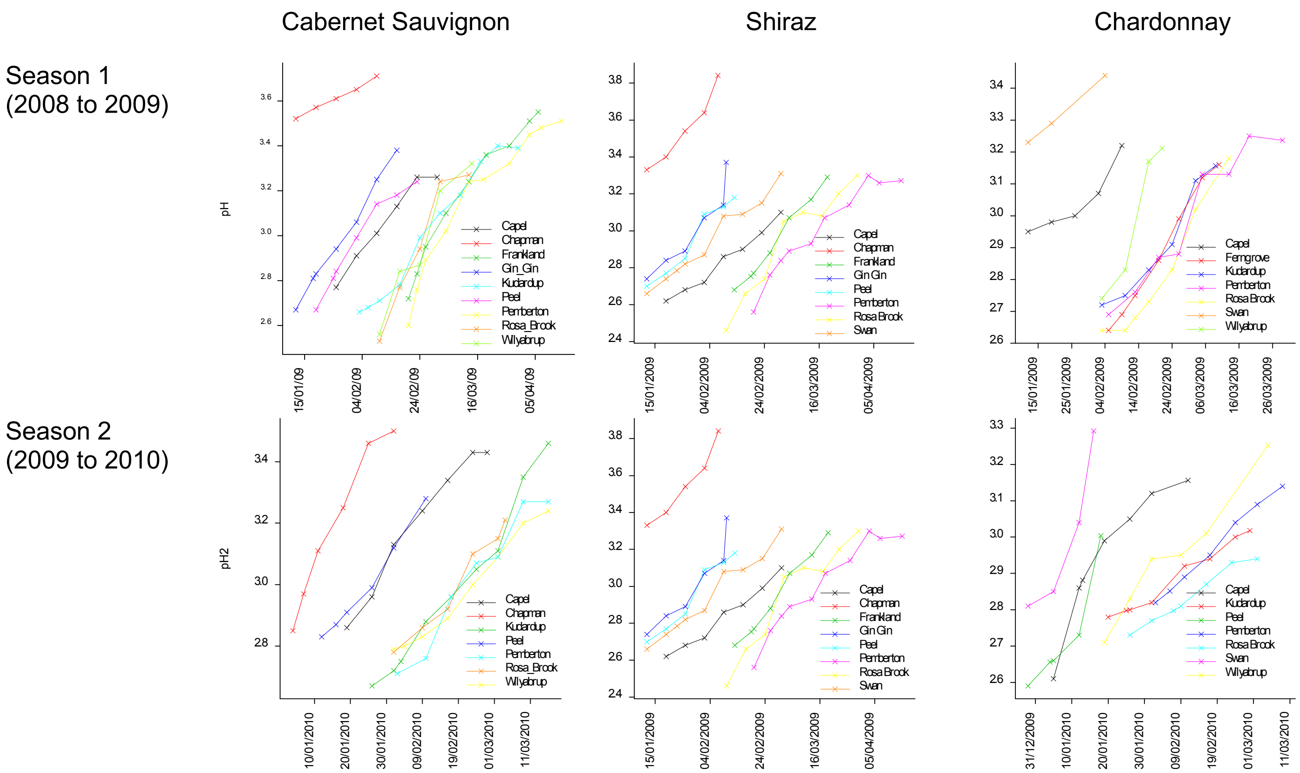
Season 2
(2009 to 2010)




Accumulation of anthocyanin concentrations (mg/g) during véraison for Cabernet Sauvignon and Shiraz. Sampling sites were represented by the names of the localities along a natural climate gradient in Western Australia.

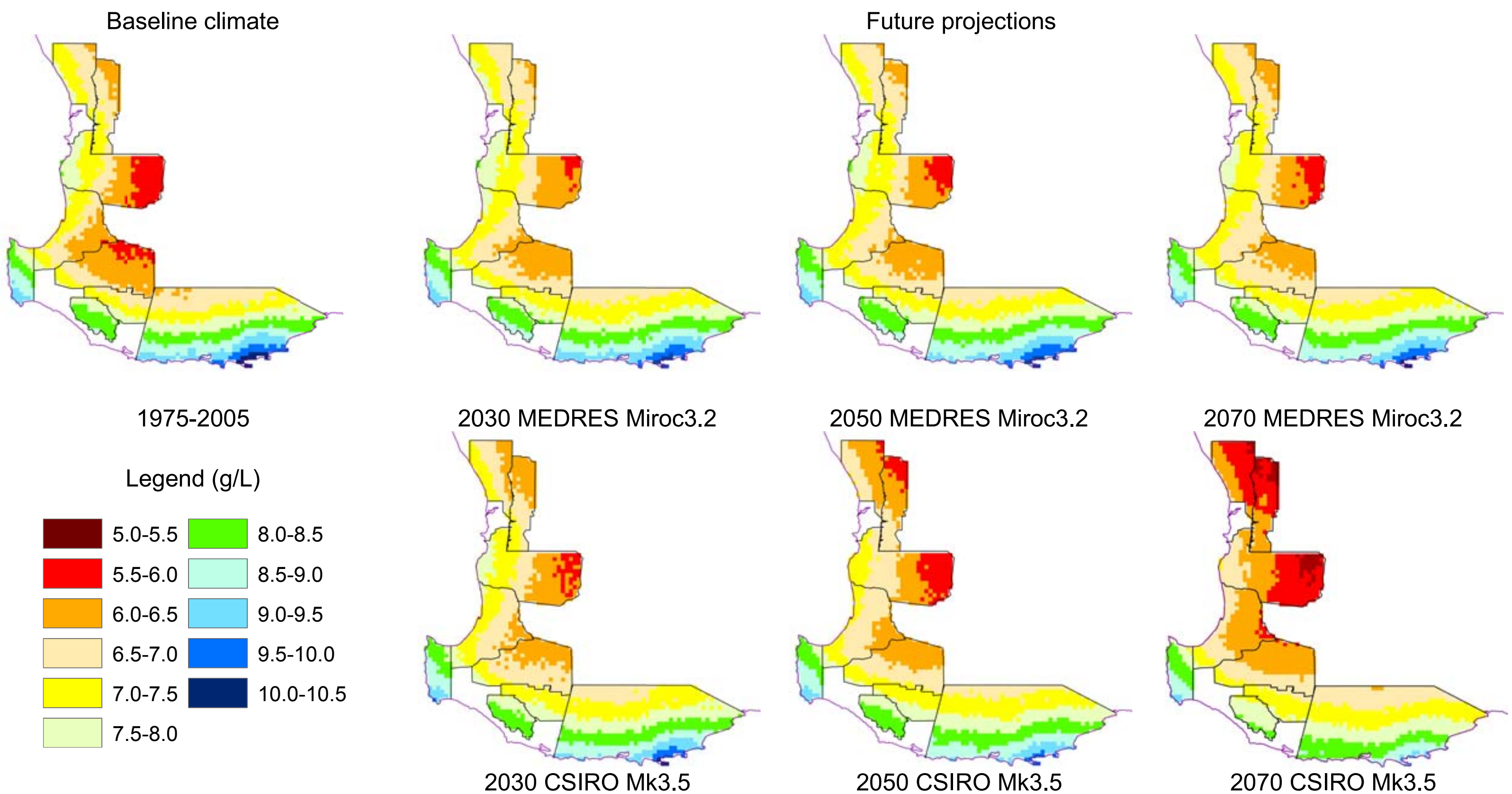



Changes in titratable acidity (in g/L) during véraison for Cabernet Sauvignon, Shiraz, and Chardonnay. Sampling sites were represented by the names of the localities along a natural climate gradient in Western Australia.

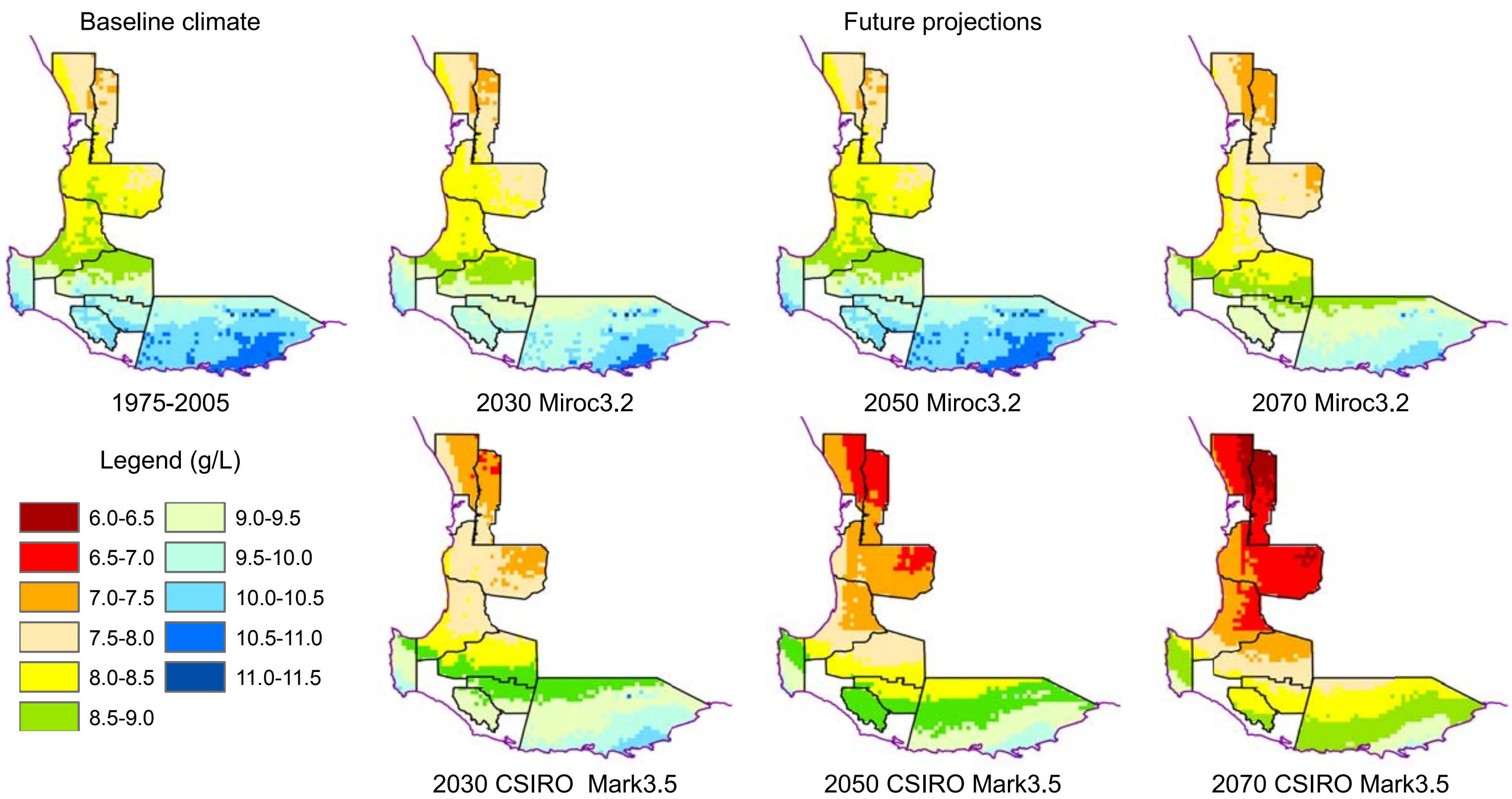



Changes in pH levels during véraison for Cabernet Sauvignon, Shiraz, and Chardonnay. Sampling sites were represented by the names of the localities along a natural climate gradient in Western Australia.

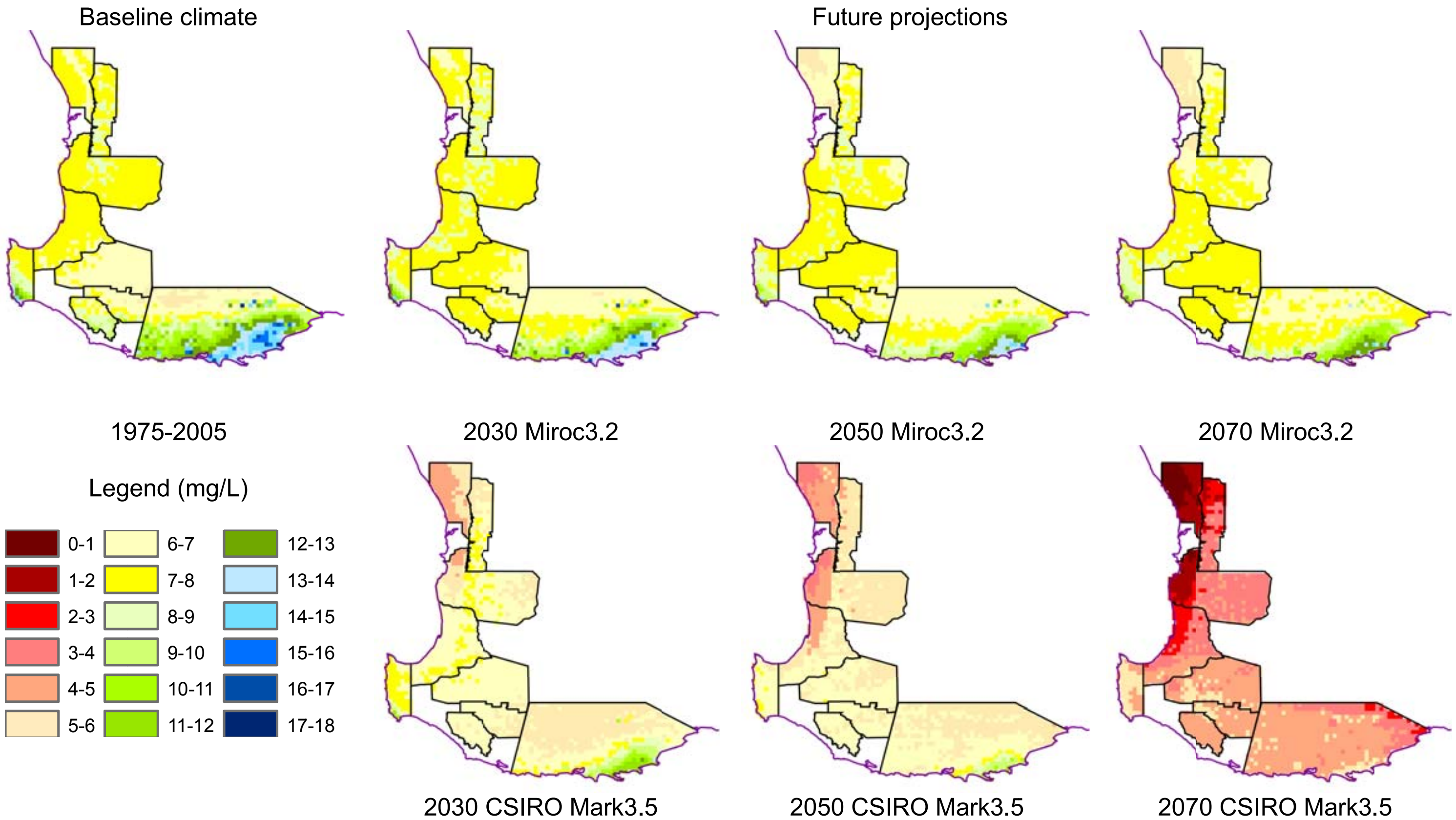
Appendix 3. Projected titratable acidity surfaces at total soluble solids (TSS) of 22 °Brix maturity under climate change



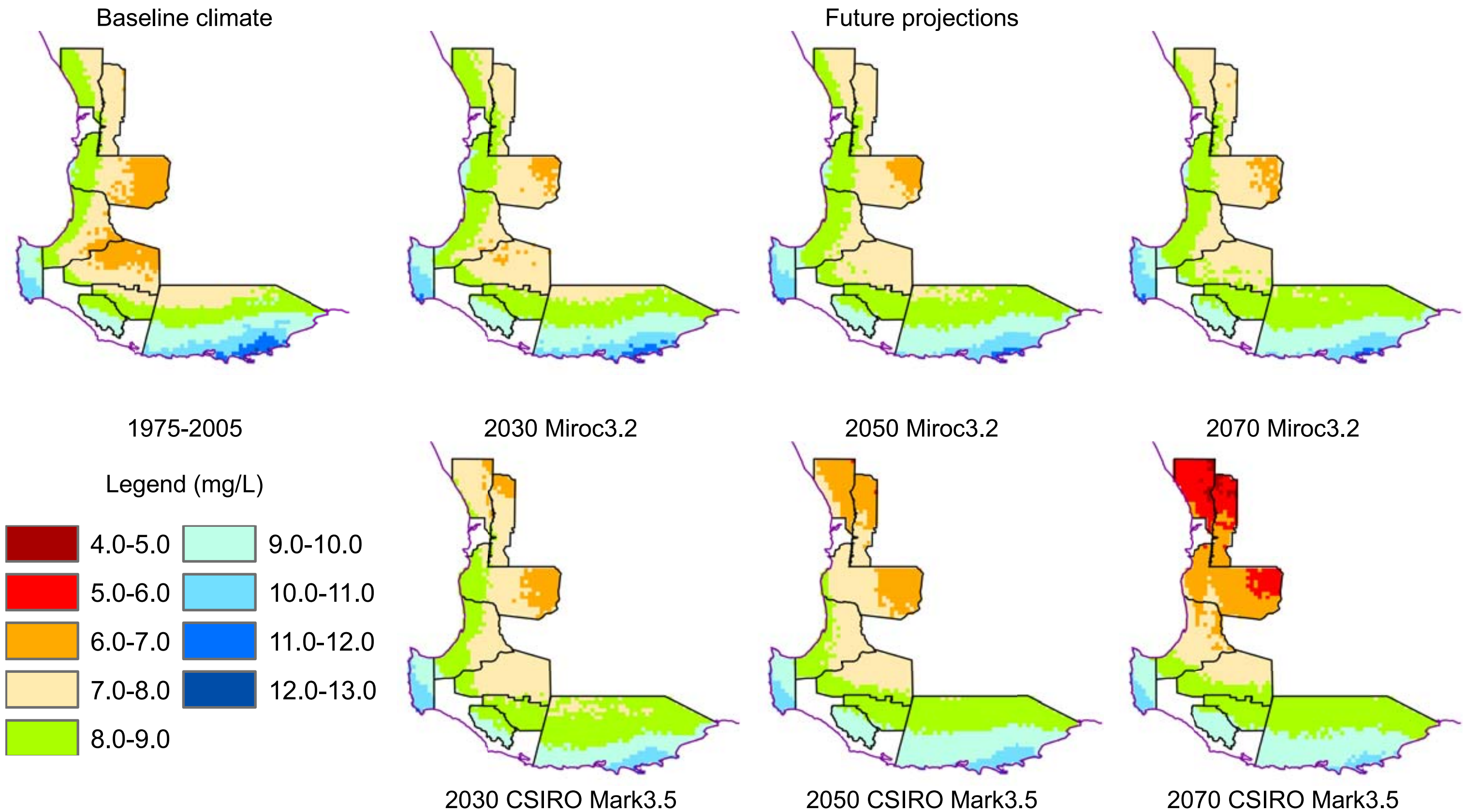

Modelled Cabernet Sauvignon titratable acidity at TSS of 22 °Brix maturity. Sum of growing degree days, diurnal range, and rainfall during growing season were used as independent climate variables for this model.




Modelled Shiraz titratable acidity at TSS of 22 °Brix maturity. Mean maximum temperature during ripening period was used as independent climate variable for this model.

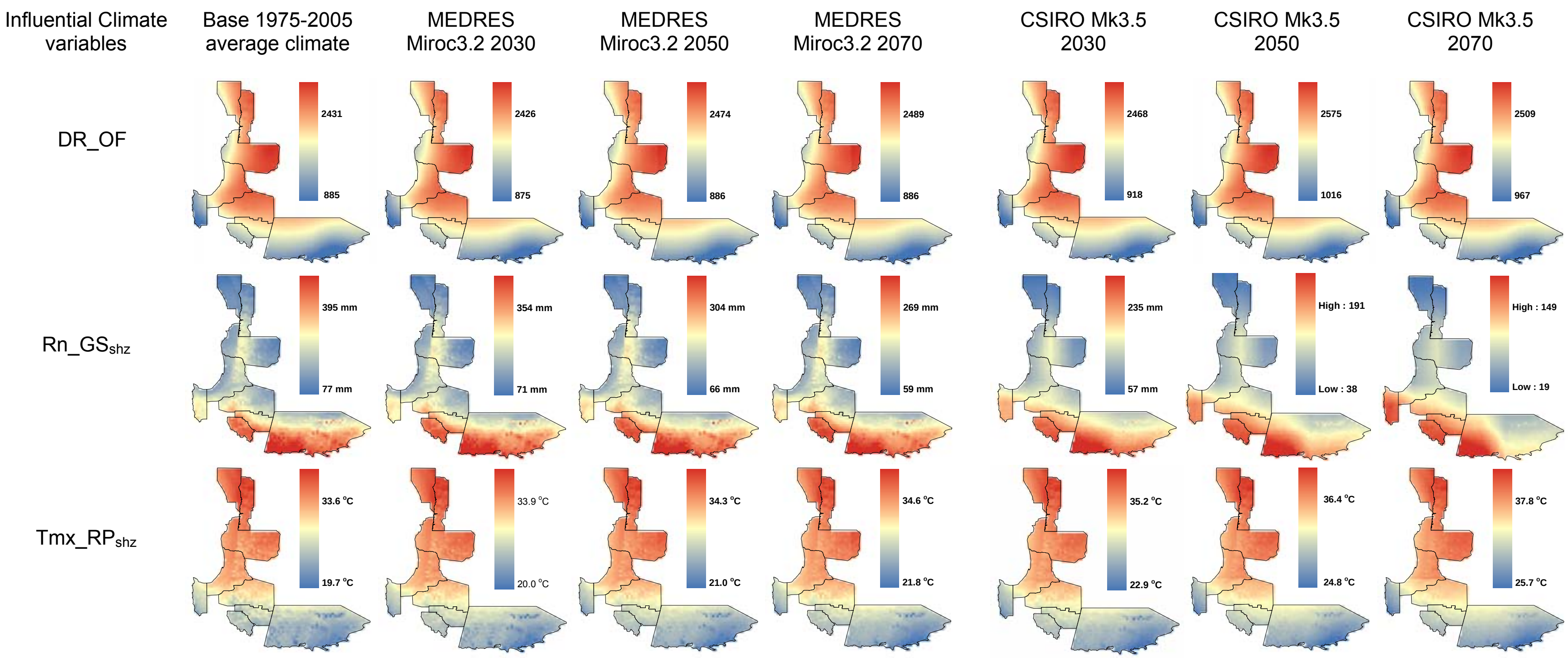



Modelled Chardonnay titratable acidity at TSS of 22 °Brix maturity. Mean minimum temperature during ripening period, number of days with maximum temperature >25°C during growing season, and November radiations were used as independent climate variables for this model.

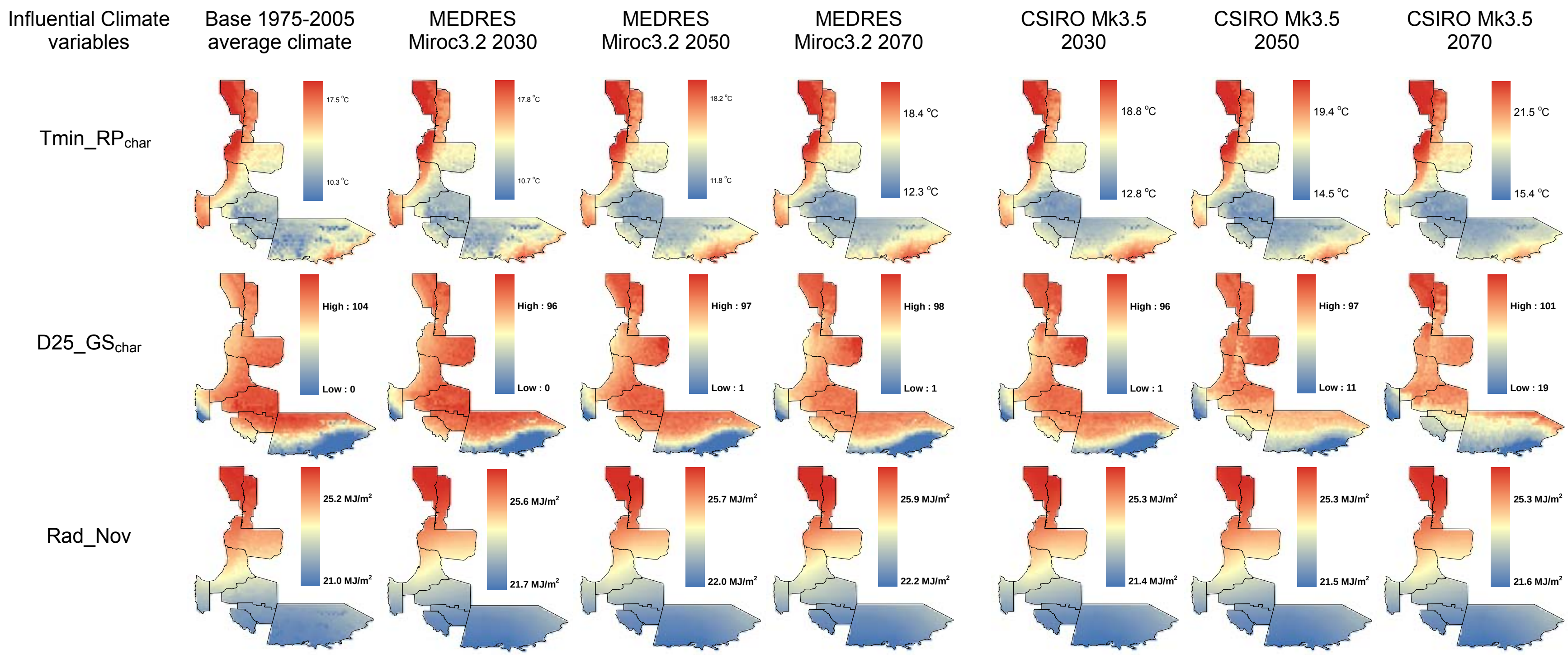



Modelled Chardonnay titratable acidity at TSS of 22 °Brix maturity. Sum of diurnal range during growing season and mean minimum temperature during ripening period were used as independent climate variables for this model.

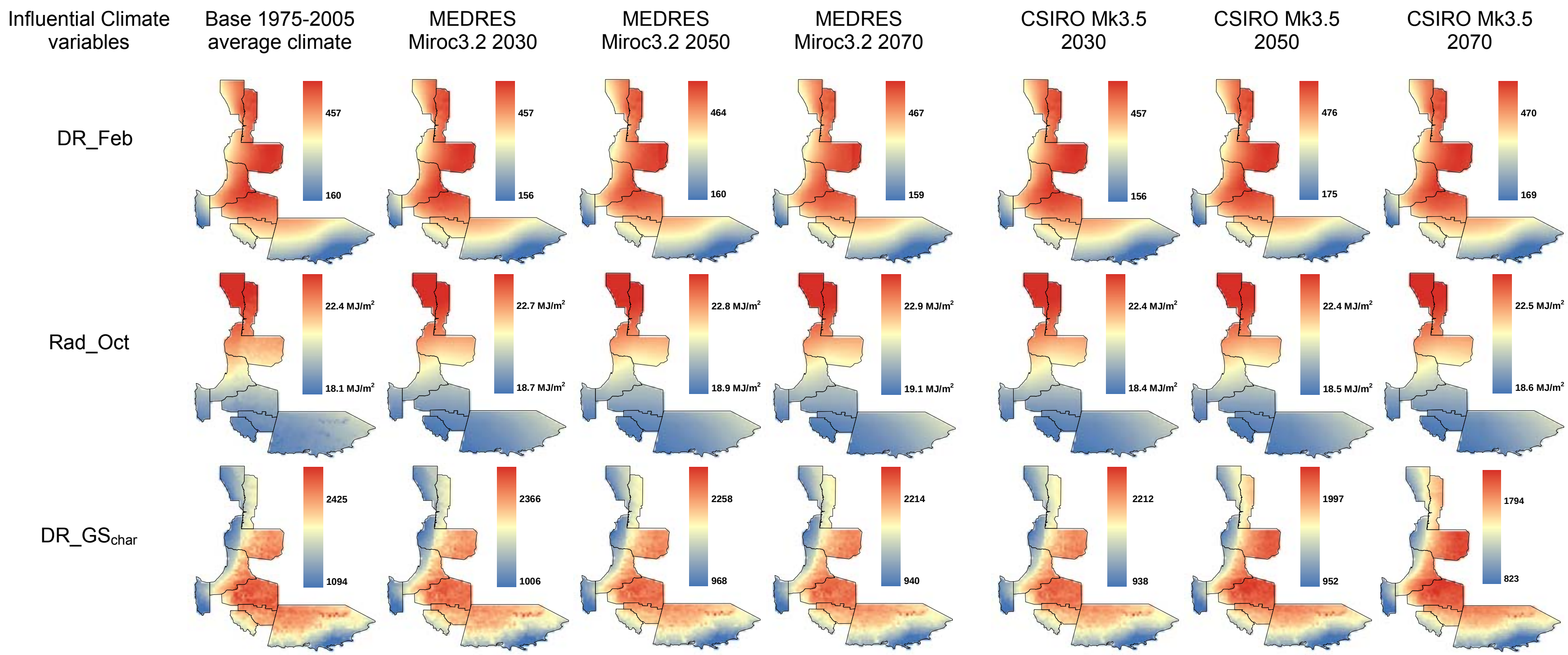
Appendix 3. Surfaces of influential climate variables used for grape quality attributes modelling at 22 °Brix total soluble maturity



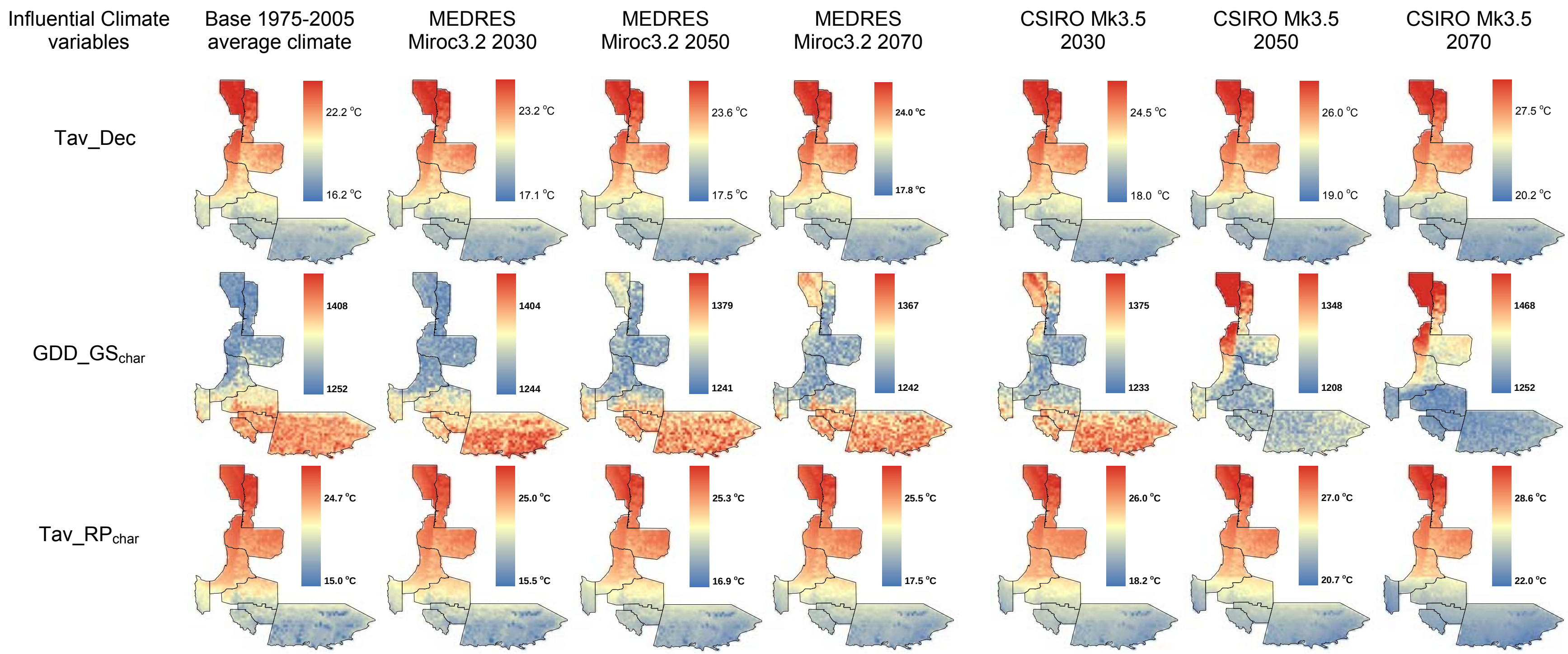

DR_OF=October to February period diurnal range, $Rn\_GS_{shz}$=Rainfall during Shiraz growing season, $Tmx\_RP_{shz}$=mean maximum temperature during Shiraz ripening period. Numbers on legend bar indicate the highest and lowest values of the variables.



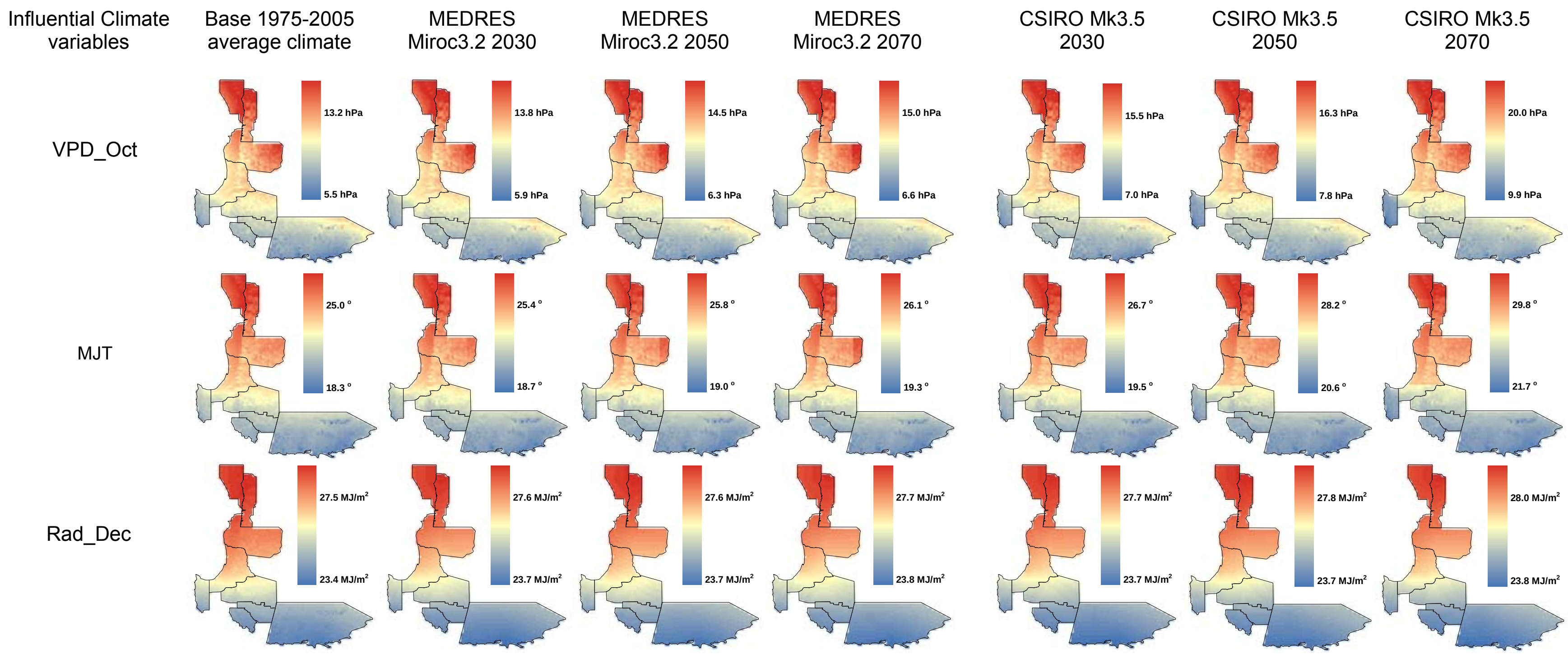

Tmn_RP$_{char}$=mean minimum temperature during Chardonnay ripening period, D25_GS$_{char}$=number of days over with maximum temperature over 25°C during Chardonnay growing season, Rad_Nov=average daily radiation in November. Numbers on legend bar indicate the highest and lowest values of the variables.




DR_Feb, $DR\_GS_{char}$=diurnal range in February and Chardonnay growing season, Rad_Oct=average daily radiation in October. Numbers on legend bar indicate the highest and lowest values of the variables.




Tav_Dec, Tav_RP$_{char}$=average temperature for December and Chardonnay ripening period, respectively, GDD_GS$_{char}$=growing degree days during Chardonnay growing season. Numbers on legend bar indicate the highest and lowest values of the variables.




VPD_Oct=vapour pressure deficit in October, MJT= mean January temperature, Rad_Dec=average daily radiation in December. Numbers on legend bar indicate the highest and lowest values among the wine regions.